Gabion Evaluation for Salmonid Enhancement in a Landslide Impacted Stream on the Queen Charlotte Islands, British Columbia

Land Management Report NUMBER 30

ISSN 0702-9861

March 1984

BC
Ministry of Forests

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Gabion Evaluation for Salmonid Enhancement in a Landslide Impacted Stream on the Queen Charlotte Islands, British Columbia

by
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March 1984

Ministry of Forests

Canadian Cataloguing in Publication Data

Klassen, Herbert D.
Gabion evaluation for salmonid enhancement in a landslide impacted stream on the Queen Charlotte Islands, British Columbia

(Land management report, ISSN 0702-9861; no. 30)

Bibliography: p.
ISBN 0-7718-8484-2

1. Artificial substrates (Aquatic biology) - British Columbia - Queen Charlotte Islands. 2. Fish habitat improvement - British Columbia - Queen Charlotte Islands. 3. Logging - Environmental aspects - British Columbia - Queen Charlotte Islands. I. British Columbia. Ministry of Forests. II. Title. III. Series.

© 1984 Province of British Columbia

Published by the
Information Services Branch
Ministry of Forests
Parliament Buildings
Victoria, B.C.
V8W 3E7

Copies of this and other Ministry of Forests titles are available at a cost-recovery price from the Queen's Printer Publications, Parliament Buildings, Victoria, B.C. V8V 4R6.

ABSTRACT

Tandem V-shaped gabion weirs for improving spawning habitat for pink (Oncorhynchus gorbuscha) and chum salmon (O. keta) in landslide-damaged streams were installed and examined in Sachs Creek, Queen Charlotte Islands. Spawner use and egg survival, as well as stability and quality of gravels entrapped by the structures were compared to that of natural control sites. Two gabion sites at 1% slope gradient attracted moderate spawner usage within weeks of installation; a third gabion site at a 3% slope gradient was beyond the upstream limit of pink and chum salmon but was used by coho (O. kisutch) spawners. Pink salmon egg survival appeared high in the first autumn and winter seasons after installation (approximately 11% to the "eyed" stage), and improvement is anticipated as the gabion sites undergo natural stabilization of streambed configurations. Gravel stability at all three gabion sites was poor over the first winter, and excessive scour threatened the integrity of the upstream, steeper slope gabion site within 1 year. However, the two gabion sites at 1% slope gradient successfully stabilized gravel over their second season of stormflows through local reductions in streambed slope gradients. The effects of gabions on gravel composition and intragravel permeability were variable. Demonstrated improvements in intragravel dissolved oxygen probably resulted from channel "roughness" added by the gabions. Intragravel dissolved oxygen had a significant ($p < .05$) positive correlation with egg survival. High juvenile coho and steelhead (Salmo gairdneri) densities at the gabion sites (average $1.6/m^2$ compared to $0.9/m^2$ at control sites) indicated high quality rearing habitat as an additional benefit. Achievement of cost effectiveness (recovery of construction costs through increases in returning adult pink salmon) was attainable in gabion sites well-used by spawners. The stability in streambed configurations provided by gabions in their second year would be useful in rehabilitating low-gradient reaches of streams damaged by landslides. Recommendations for gabion installation include their restriction to downstream reaches of less than 2% slope gradient, where moderate to heavy spawner usage would occur.

PREFACE

This paper may be of interest to foresters, fish biologists, and fisheries managers alike. The major purpose of the paper was to evaluate one method of rehabilitating a debris-torrented stream, with respect to fish production. Guidelines for gabion installation were included, as was a benefit-cost analysis. This study was designed to fulfill, in part, the requirements for the degree of Master of Science in the Department of Forestry at the University of British Columbia.

ACKNOWLEDGEMENTS

Many individuals and agencies have contributed to this project. The majority of the funding during the construction phase was provided by the multi-agency sponsored Fish/Forestry Interaction Program (FFIP). The agencies included B.C. Ministry of Forests, B.C. Ministry of Environment, and Canada Department of Fisheries and Oceans. Funding in the second year was through a Program of Research by Universities in Forestry (PRUF) grant, sponsored by the Canadian Forestry Service. Other significant contributions are gratefully acknowledged: D. Kendall, D. Kendall and Sons, Queen Charlotte City; P. Slaney, B.C. Fish and Wildlife Branch, Vancouver; J. Conners, MacMillan Bloedel, Jaskatla Division; G. Brennenstuhl and R. Frank, Crown Forests, Sandspit; F. Beban, Westrock Contracting, Sandspit; and G. Derksen, EPS, Vancouver. Manpower assistance so critical to this project was provided by the Fisheries Employment Bridging Assistance Program. The illustrations enclosed were drafted by FFIP office staff provided by the Department of Fisheries and Oceans; L. White, D. Dimoff, A. Brattkus, D. Day, and S. Parker. Technical assistance in evaluating the gabions was provided by D. Bouillon, J. Ellis, and M. Morris.

Helpful on-site suggestions were received from Dr. L. Beaven, L. Dutta, B. Eccles, E. Harding, J. Lamb, K. Moore, and D. Tripp. Thanks to FFIP's Technical Advisory Committee (T. Baker, M. Brownlee, A. Cowan, T. Dyer, J. Lamb, K. Moore, L. Powell, J. Schwab, J. Walker, V. Wellburn, and D. Wilford) for program direction and the editing of previous drafts. Appreciation for academic advice, the generous use of equipment, and editing previous drafts is extended to my thesis committee: Dr. T.G. Northcote, Supervisor; Dr. M. Feller; Dr. D. Golding; Dr. G. Hartman; V. Poulin; and P. Slaney. Special thanks to FFIP program manager V. Poulin, without whom this project would not have been possible.

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1 INTRODUCTION

Coastal forest harvesting and salmonid fisheries have conflicting resource uses that have been recently receiving increased attention from resource managers and the public. Lack of knowledge of harvesting impacts on the fisheries resource has stimulated many investigations, most notably the intensive studies on the Alsea watershed, Oregon (Moring 1975), and on the Carnation Creek watershed, Vancouver Island (Hartman 1982). One problem not satisfactorily dealt with in these studies is the effect of mass wasting on the fisheries resource.[1] Steepland logging has accelerated the rate of landslides in the coastal mainland (Mersereau and Dyrness 1972; O'Loughlin 1972; Swanston and Swanson 1976) and particularly in the Queen Charlotte Islands (Wilford and Schwab 1982).[2] The negative impacts of landslides on fish-bearing streams have been quantified in Oregon (Everest and Meehan 1981) and Washington (Cederholm and Salo 1979). The most destructive type of landslide from a fisheries perspective is the debris torrent, which destabilizes streams causing the original meandering channels to give way to more chute-like channels devoid of the integral logs which provide stream diversity and stabilized pockets of spawning gravels and rearing areas. The impetus for this study lies in the need to develop applied restoration techniques for salmonid spawning streams damaged by landslides on the Queen Charlotte Islands.

Many factors contribute to low early survival of pink (Oncorhynchus gorbuscha) and chum (O. keta) salmon stocks. Egg-to-fry survival has often been as low as 5% for wild salmonids (Dill 1969; McNeil 1969; Langer 1974), owing to drought, predators, over-population of spawning areas, and

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1 J. Hall. Quoted in: G.F. Hartman (editor). Carnation Creek Workshop. Malaspina College, Nanaimo, B.C. April 1982. p. 401.

2 In preparation: P. Gimbarvesky. [1983]. A regional overview of mass wasting on the Queen Charlotte Islands; and K.M. Rood. [1984]. Logging landuse and mass wasting on the Queen Charlotte Islands. Fish/Forestry Interaction Program, Vancouver, B.C.

sedimentation (Wickett 1958; Shelton and Pollack 1966; Bjornn 1968; Koski 1975; Slaney et al. 1977; Cederholm and Salo 1979). Gravel scour has also been shown to affect salmonid egg survival. During stormflow events, entire stocks of chinook salmon (O. tshawytscha) have been destroyed by scour (Gangmark and Bakkala 1960). Similarly, McNeil (1966) attributed a 90% loss of pink and chum salmon eggs to a single stormflow event; he suggested that mortality was caused by both mechanical abrasion and stream flushing action, which removed embryos from the protective gravel.

Debris torrents and streambank logging practices intensify gravel scour by reducing the frequency of "organic steps" described by Heede (1972), thereby increasing streambed gradients and stormflow velocities. Reductions in stable large organic debris decreased both channel "roughness" and abundance of gravel associated with the debris (Swanson et al. 1976). Additional streambed instability and degradation may have resulted from sediments released from damaged banks or depositional zones of landslides.

Recent developments of in-stream structures have successfully produced stabilized spawning areas (Hall and Baker 1982). Gabion weirs (wire cages that are placed into the stream bottom and filled with small rocks) were one of several stream rehabilitation techniques recommended for evaluation in the Queen Charlotte Islands by the Fish/Forestry Interaction Program (FFIP)[3] (Bustard 1983). Gabion weirs can stabilize gravel movement by impounding gravels and reducing stormflow energy (Gerke 1974). Gabions have been found to reduce streambed gradient and to impound gravel beds with a mean particle size typical of salmonid spawning areas (Moreau 1981). Furthermore, the depth of gravel scour can be reduced by subsequent reductions in stormflow shear stress at the surface of the impounded gravels (Lisle 1981).

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[3] The FFIP is a multi-agency sponsored investigation into the extent, causes, and amelioration of landslide damage in forests and streams of the Queen Charlotte Islands. The program was contracted to V.A. Poulin & Associates Ltd. of Vancouver B.C. One aspect of FFIP undertaken by the author was to evaluate gabions as a rehabilitation technique for landslide-damaged streams.

The specific objectives of this study were to 1) examine the effectiveness of gabions in improving gravel quality (dissolved oxygen, permeability, gravel composition, and depth of scour), as well as the early survival of pink and chum salmon under conditions typical of the Queen Charlotte Islands; and 2) identify spawning gravel characteristics related to early survival in pink and chum salmon.

2 THE STUDY AREA

Sachs Creek on the northeast end of Moresby Island was selected as the study stream for this project. In his review of stream rehabilitation techniques for FFIP, Bustard (1983) recommended Sachs Creek for gabion evaluation. It was considered the most suitable stream for several reasons:

i. The stream lies in close proximity to sources of manpower, equipment, and gravel supplies.

ii. The stream was the site of previous salmonid enhancement work by MacMillan Bloedel. Hence, there was interest in further restoration work there.

iii. The stream had a major debris torrent in 1974, depositing tonnes of material just upstream of salmon spawning habitat. Release of entrapped sediments after mechanical removal of the terminal log jam by the Federal Department of Fisheries and Oceans in 1978 has subsequently destabilized the stream, as evidenced by active lateral channel migration for several hundred metres downstream. This lateral erosion and excessive sediment transport is similar to many other landslide-damaged streams.

iv. The stream size is acceptable for in-stream work and studies, having an average wetted width of 10 m and a summer discharge of about 0.07 m^3/sec (2-3 ft^3/sec).

v. The stream supports significant runs of pink, chum, and coho (O. kisutch) salmon, and a small run of steelhead trout (Salmo gairdneri).

Sachs Creek drains into Skidegate Inlet on the northern end of Moresby Island and is about 11 km long within a 19-km^2 watershed (Figure 1). Its bedrock type is mainly sedimentary. The streambed slope gradient averages 1% for the lowermost 1 km, 2% for the next 1 km, 3% for the next 0.5 km, then rises sharply upstream through a canyon (Figure 2). The stream discharge averages about 0.3 m^3/sec (12 ft^3/sec) during the fall, with stormflow discharge up to about 65 m^3/sec (2300 ft^3/sec) based on unmetred calculations (Manning's Equation).

From late August through November, Sachs Creek supports runs of adult chum, pink, and coho salmon successively. Pinks and chum spawn in the lower 1.5 km with maximum density from 0.6 km to 0.8 km above the estuary (Figure 16). Coho distribute themselves more evenly through the lower 2.5 km upstream to the canyon barrier. Pink salmon exhibit a two-year cycle, with even years having dominant runs typical of most Queen Charlotte Islands streams. "Even year" pink salmon escapements have historically ranged from about 200 to 30 000, with a mean of about 4600 (Figure 3). Recent escapements have been about 3000 to 4000. Adult chum escapements historically have ranged from about 25 to 1500; however, they have seldom exceeded 200 in the past decade. Estimated coho escapements have rarely been in excess of 200 adults.

Sachs Creek watershed lies mainly within MacMillan Bloedel's TFL 39, with about 5% in Crown Forest's TFL 2. About 40% of the watershed has been logged since the early 1960's (Figure 4).

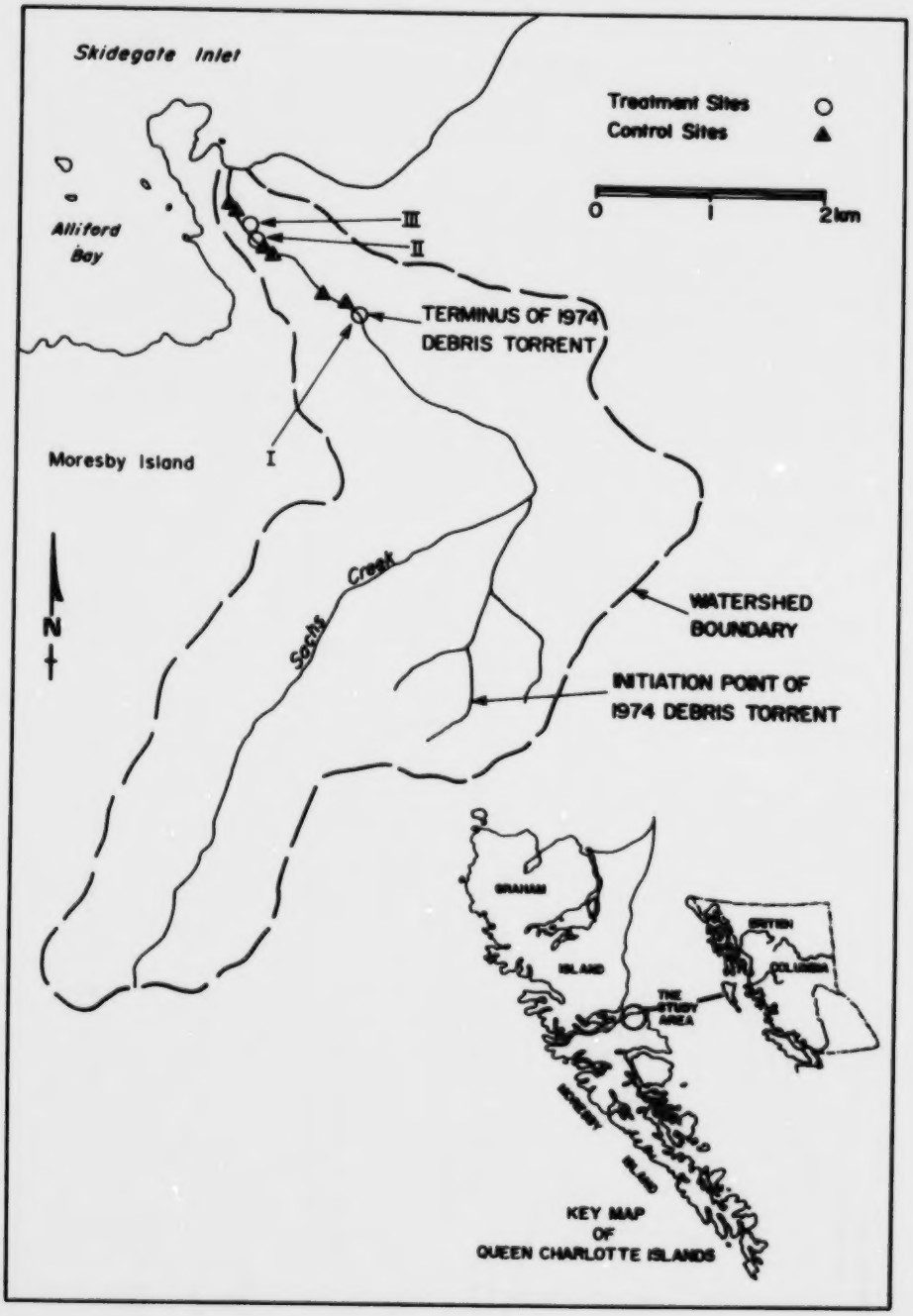

FIGURE 1. Site locations on Sachs Creek.

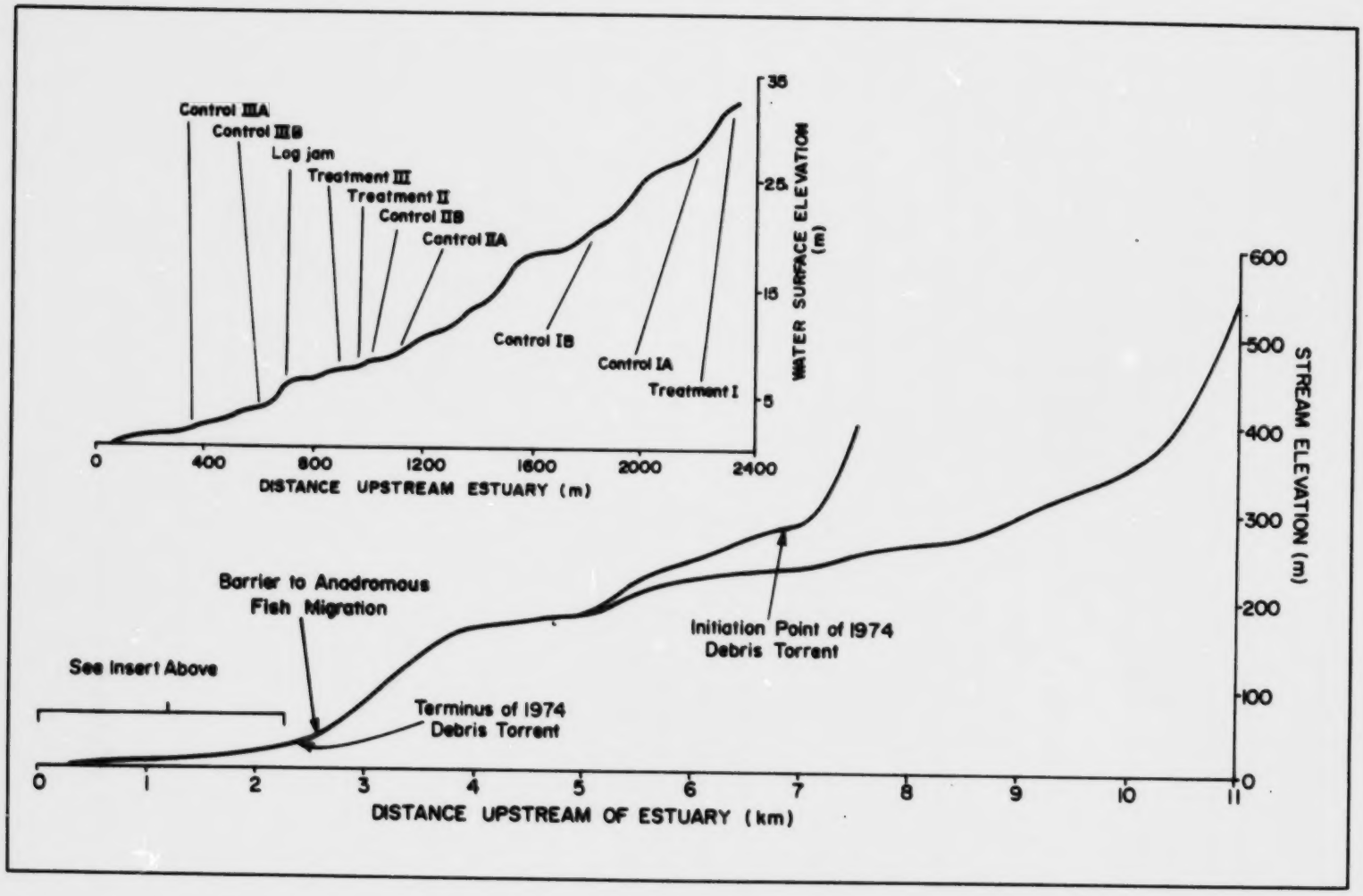

FIGURE 2. Longitudinal profile of Sachs Creek.

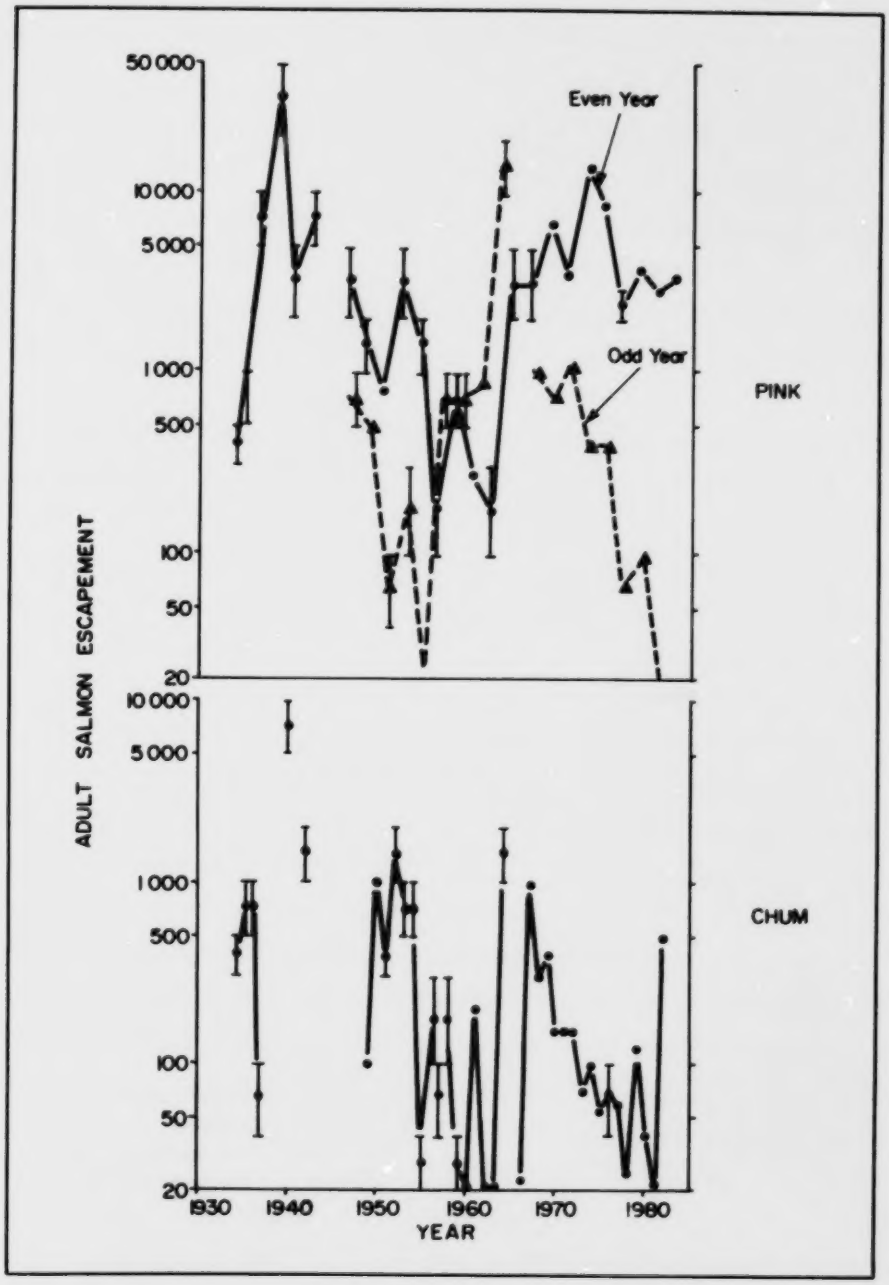

FIGURE 3. Estimated spawner escapements at Sachs Creek.[a]

[a] Federal Dept. Fisheries and Oceans records.

FIGURE 4. Logging history of Sachs Creek.

3 METHODS

Three sites on Sachs Creek were selected for gabion installation. Gabions were installed in pairs at each of the three treatment sites and were matched with two control sites to enable statistical evaluation of tne results. The approach to evaluating gabions involved three main phases:

i. Pre-installation site analysis, including stream and site selection, site surveying, intragravel dissolved oxygen, and permeability sampling.

ii. Gabion construction and installation, involving eight men and heavy equipment.

iii. Post-installation site analysis, including monitoring of salmon spawner use, configurational changes in gravel, measurements of substrate stability, gravel quality, and salmon egg survival.

The project was initiated in May 1982 with reconnaissance surveys of potential sites on various Queen Charlotte Islands streams. Final site selection, pre-installation sampling, and surveying were completed in July 1982. The construction-installation phase was conducted during the month of August 1982. Parameters noted above were remeasured at 0.5-year, 1-year, and 1.5-year intervals after installation.

3.1 Gabion Description

Gabions (0.91 m high by 0.91 m wide) consisted of galvanized steel twisted mesh (3 mm diameter, 8 x 10 cm aperture) manufactured by Maccaferri Gabions. Combinations of gabions 1.82 m, 2.73 m, and 3.64 m long were wired together to span the stream (see 3.4.1 and 3.4.2).

3.2 Study Site Locations

Study sites were selected largely based on the criteria developed in Northern California (Moreau 1981). In brief, these criteria included: 1) adequate road access, 2) a straight section of stream channel, and 3) a wide floodplain with shallow banks. Three treatment sites were selected, each representing different habitat configurations. Treatment Site I was

located 2300 m upstream of the estuary at the point of egress of the 1974 debris torrent (Figures 1 and 2) in a riffle at the tail of a pool. Treatment Site II was situated in a 60 m riffle 950 m from the estuary. Treatment Site III was in a deeper, slow moving (glide) section of the stream 880 m above the estuary. All sites met the recommended criteria and were considered marginal spawning habitat; i.e., the sites lacked suitable spawning substrate, having mean particle diameters considerably larger or smaller than the 25 mm found in the top layers of Carnation Creek chum salmon spawning areas (Scrivener and Brownlee 1982).

Two control sites were selected for each treatment site in order to apply paired t-tests for statistical analysis. One control ("A" - poor spawning habitat) was selected to resemble the particular treatment site before the gabions were installed. The second control ("B" - prime spawning habitat) was selected a priori to resemble the treatment site after the gabions were installed. This was accomplished by selecting 20-m long riffles at the tails of pools having either 1) poor spawning conditions or 2) suitable water depth, velocity, and substrate for spawning. Criteria for suitable spawning conditions approximated high probability-of-use values (see 3.5.2, 3.5.3, and Appendix 1). Only minimal influences of gabion installation were anticipated on these control sites. Two methods of parameter comparison between the treatment and the control sites (both types 1 and 2 of control where possible) were used. First, mean values of the variables were calculated for each site. Second, individual sample points within the treatment sites, based on distance downstream of the initial pool and distance from either streambank, were paired with representative points in the control sites. A portable grid system using benchmarks on either bank facilitated this comparison. Statistical analysis using the two types of control sites provided a more rigorous comparison than using before-and-after comparisons without controls.

3.3 Pre-Treatment Site Analysis

Intragravel permeability and dissolved oxygen, gravel composition, and streambed topography were measured prior to gabion installation.

Measurement of the above variables was done on a stratified grid system rather than on a randomly selected basis. The stratified design enabled values at points in treatment sites to be paired with those in control sites for t-test analysis. Intragravel dissolved oxygen was determined from 18 to 21 100-mL samples per site of intragravel water extracted from 25 cm below the gravel surface with a stainless steel syringe. Dissolved oxygen in these water samples was immediately measured with regularly calibrated oxygen meters from the Yellow Springs Instrument Co. Semi-micro Winkler titrations (Rand et al. (editors) 1975) were used for further calibration of the oxygen meters.

Intragravel permeability was measured using a Mark VI standpipe (Terhune 1958). This technique operated on the principle of measured flow into a pipe through perforations 25 cm below substrate surface. The driving force was a negative pressure head of 2.5 cm, provided by a hand suction pump in the pipe. Between 15 and 21 measurements were made per site.

Stream bottom contours were determined to evaluate the anticipated changes in their configuration due to gabion placement. The treatment site elevations were surveyed by theodolite (Wild). Measurements were made on approximately 60 stations within the grid systems, as well as on cross sections at 10-m intervals.

Stream gravel was sampled at the gabion sites with two techniques to enable comparison with gravel composition at the sites after gabion placement. The stations sampled were stratified (using the grid system) across the width of the stream, and 2 m upstream of the future locations of lower gabions. For pre-installation analysis, seven gravel samples were taken in Treatment Site III using a McNeil gravel sampler (Cederholm and Salo 1979). Gravels at Treatment Site II were sampled by two techniques: each sample taken with the McNeil gravel sampler was matched with a freeze-core sample (Scrivener and Brownlee 1982). Gravel composition was analyzed using 18 sieve sizes to accurately indicate composition of fines. The large substrate size at Treatment Site I (pre-installation) precluded sampling by either method. Hence, four

randomly selected stations at Treatment Site I were photographed for later analysis. The analysis involved calculating surface particle diameter frequencies from 140 (random) measurements, using the photographic slides projected to actual size.

3.4 Gabion Construction and Installation

Selection of a gabion configuration followed review of several tested in Washington, Oregon, and California (Gerke 1974; Engels 1975; Anderson and Cameron 1980; Anderson 1981; Moreau 1981; Ward 1982). Moreau (1981) in California found that a paired V-shaped configuration was the most successful design in trapping bedload suitable for salmonid spawning and for withstanding stormflows. This configuration was used at all treatment sites in this study, with some minor modifications (Figure 5). Splash aprons were modified to maximize the depth of the plunge pool created at the downstream edge of the gabions. The modification was made to prevent undercutting the gabion, while facilitating adult migration. The splash aprons measured 0.30 m high by 0.91 m wide by 1.82 m long, and were installed underneath the gabion, but extending approximately 0.6 m beyond the gabion to form a scour-resistant platform at the base of the gabion apex (Figure 5).

Gabions were positioned to allow adult salmon migration but prevent lateral bank scour (Moreau 1981). The top of the upstream gabion was positioned 50 cm above that of the original streambed. To achieve this height, the streambed was excavated to a depth of 50 cm, and to 90 cm in the region of the splash aprons. The elevation of the downstream gabion was calculated from criteria given by Moreau (1981) and Reeves and Roelofs (1982); i.e., the top of the downstream gabion was level with the base of the upstream one. Although surveying techniques were used, the actual placement varied up to 10 cm from these guidelines. Gabion trenches were excavated to provide an 8-15 cm drop along the top of the gabions from the streambank to the apex, thus ensuring concentrated waterflow for fish passage during critical summer low flows.

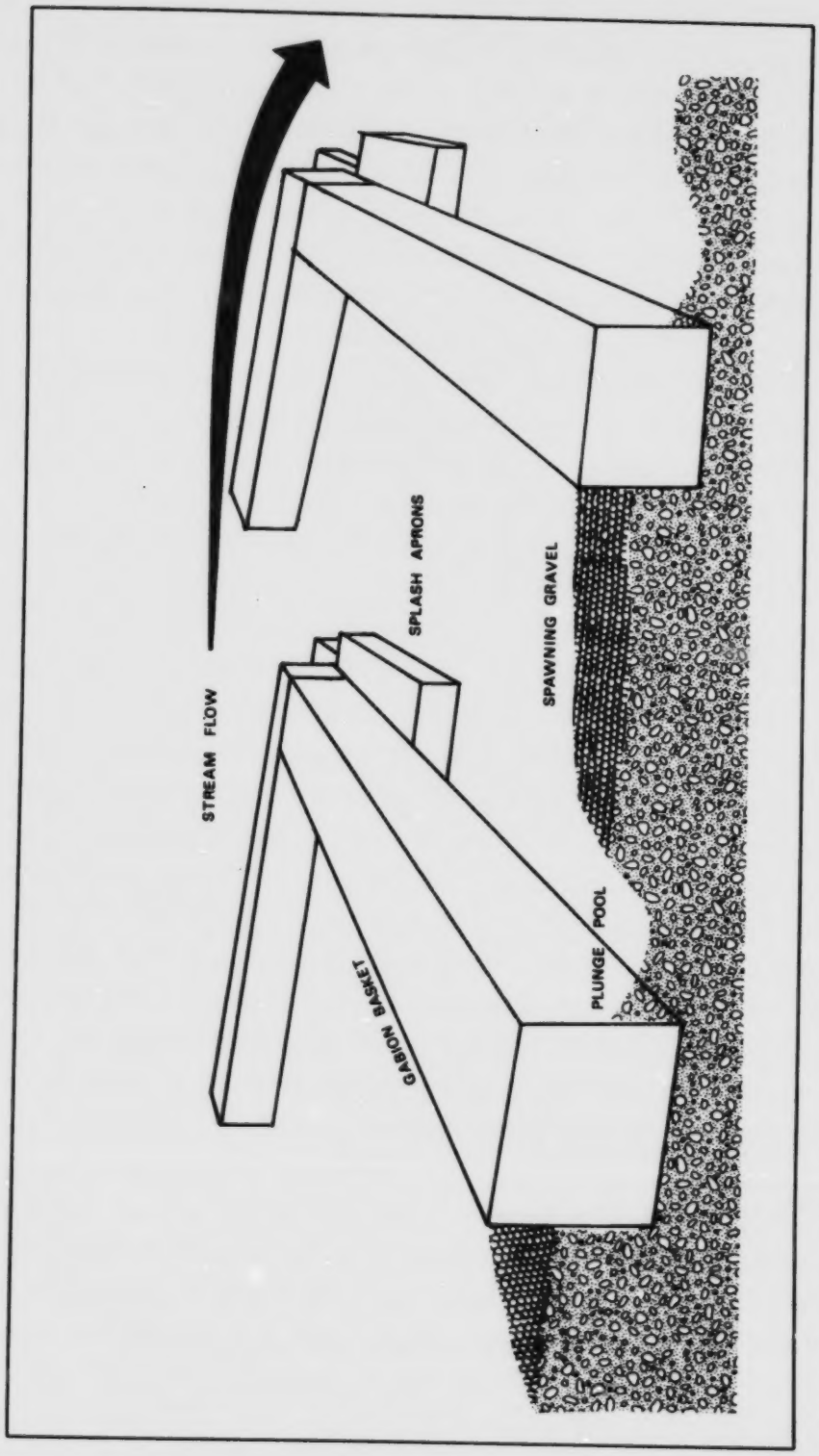

FIGURE 5. Generalized view of gabion configuration.

Similarly, horizontal placement of the gabions followed recommendations by Moreau (1981). Recommended angles between the wings of the gabions varied from 90 to 120° -- the sharper the angle, the less resistance to stormflows. Sufficient distances between the gabions were selected to enable proper elevational positioning after accounting for streambed gradients. The gabion ends were buried up to 4 m in the streambanks, and protected by riprap. Specific characteristics of the horizontal placement are described for each site in 3.4.1, 3.4.2, and 3.4.3.

To permit site usage by a large run of pink salmon anticipated in fall of 1982, gabion sites were surcharged (i.e., filled to a height level with the top of the gabions) with gravel suitable for spawning. Approximately 300 m^3 per site of unsorted "river run" gravel was delivered from a nearby quarry.

Additional manpower and heavy equipment were required in gabion construction and installation. Seven men were available through the Fisheries Employment Bridging Assistance Program; crew size varied from one to five during this phase. The heavy equipment used to excavate gabion sites was supplied by a local contractor. The equipment supplied included a 12-yd^3 dump truck; a 2-yd^3 front end loader; a 22-tonne, 1 1/4-yd^3 bucket excavator; and a 3/4-yd^3 bucket excavator. Gabion construction and installation was carried out in 20 steps to minimize costly "idle equipment" time (Figure 6).

In-stream work was carried out under guidelines and the permission of the local Department of Fisheries and Oceans, and Provincial Fish and Wildlife offices. Standard procedures outlined here restricted work to low-flow periods and periods when there were no spawning salmonids, developing eggs, or larvae in the system.

3.4.1 Treatment Site I

The inter-gabion distance selected for this site was 6.5 m, largely based on suitability of the streambank for keying in the gabions. An apical angle of 90° was used (Moreau 1981). Three of

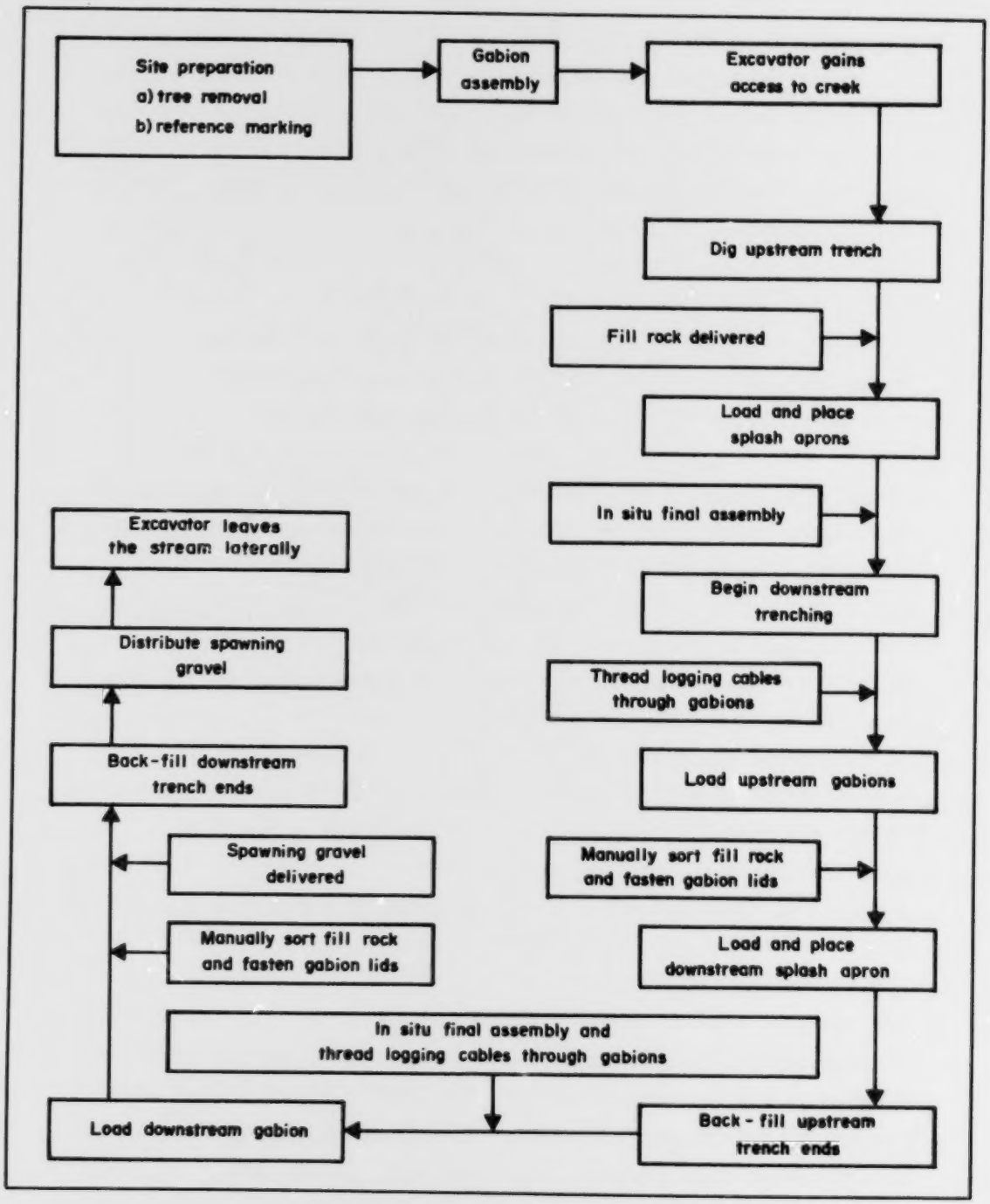
Site preparation
a) tree removal
b) reference marking
Gabion assembly
Excavator gains access to creek
Dig upstream trench
Fill rock delivered
Load and place splash aprons
In situ final assembly
Begin downstream trenching
Thread logging cables through gabions
Load upstream gabions
Manually sort fill rock and fasten gabion lids
Load and place downstream splash apron
Back-fill upstream trench ends
In situ final assembly and thread logging cables through gabions
Load downstream gabion
Back-fill downstream trench ends
Spawning gravel delivered
Manually sort fill rock and fasten gabion lids
Distribute spawning gravel
Excavator leaves the stream laterally

FIGURE 6. Flow diagram of gabion installation.

the gabion ends were buried 2 m to 4 m into the streambank; the fourth was butted up and cabled to a stable log 1 m into the bank. The gabion length required was 43 m. An abundant supply of riprap was available on this previously destabilized site; hence all the banks were left well armoured. Commercially sorted gabion fill rock was not required on this site.

3.4.2 Treatment Site II

The inter-gabion distance selected for this site was 10.5 m with an apical angle of 90°. All four gabion ends were buried 3 m to 5 m into the streambank. The total gabion length required was 50 m. Natural riprap was available to protect the ends of the upstream gabion only. Bank scour from the fall 1982 stormflows at the downstream gabion ends (not protected by riprap) was later stopped by handplacing large alder root wads and securing them with logging cables and riprap. Commercially sorted gabion fill rock (15-30 cm diameter) was required at this site because of a lack of suitable natural material. In addition, 21 m^3 of commercially sorted "drain rock" of 2-15 cm diameter was distributed over the spawning platforms to dilute the proportion of fines in the river-run gravels used to surcharge the sites. (The fines less than 2.4 mm were diluted to 9% of gravel composition samples with the addition of drain rock. The amount of fines was greater where no drain rock was applied -- 11% and 19% for Treatment Sites I and III, respectively; see Figure 13.)

3.4.3 Treatment Site III

An inter-gabion distance of 10.5 m was used. The apical angle of 120° was selected to enlarge the area of the spawning platform created by the downstream gabion. Three of the gabion ends were buried 2-4 m into the streambank. The fourth gabion end was butted up and cabled onto a stable log. The total gabion length required was 35 m. Natural riprap was lacking at this site, so the streambanks were initially left unprotected. Lateral bank scour during fall stormflows prompted handplacement of riprap at these gabion ends.

3.4.4 Site revegetation and bank stabilization

Streambank modification was considerable during gabion installation, especially where trenches extended deep into the banks. Although the trenches were backfilled and piles of excavated material smoothed, areas along the bank for the length of the sites were left with bare mineral soil. To facilitate streambank recovery, several steps were taken following construction:

i. Banks at Treatment Sites II and III were hand seeded with a grass-legume mix. Treatment Site I was left as a control.

ii. A total of 90 juvenile alders, hemlock, and forbs were planted with a 2-m spacing on the banks of Treatment Sites II and III.

iii. A layer of seaweed mulch was distributed on Treatment Site II to serve as both fertilizer and act as a soil binder upon decomposition.

3.5 Post-Installation Site Analysis

3.5.1 Gravel stability

Depth of gravel scour was closely monitored as a measure of gravel stability in the three treatment and three or four control sites over the winter of 1982 and the fall and winter of 1983-84. Approximately 20 vertical erosion monitors (VEM's) were installed at each of these sites in December 1982, and again in August and/or October 1983. The VEM's employed consisted of a column of eight perforated plastic golf balls threaded through with 100-lb (45-kg) test monofilament line. The assembly was inserted vertically into the gravel with the method illustrated in Figure 7. A plastic disc at the distal end of the 1.5 m long monofilament prevented loss of balls released by scouring. The number of balls scoured out of the gravel after a stormflow event was used as a measure of the depth of scour at that location. The depths of scour at individual stations at treatment sites were paired with that at control sites for t-test analysis.

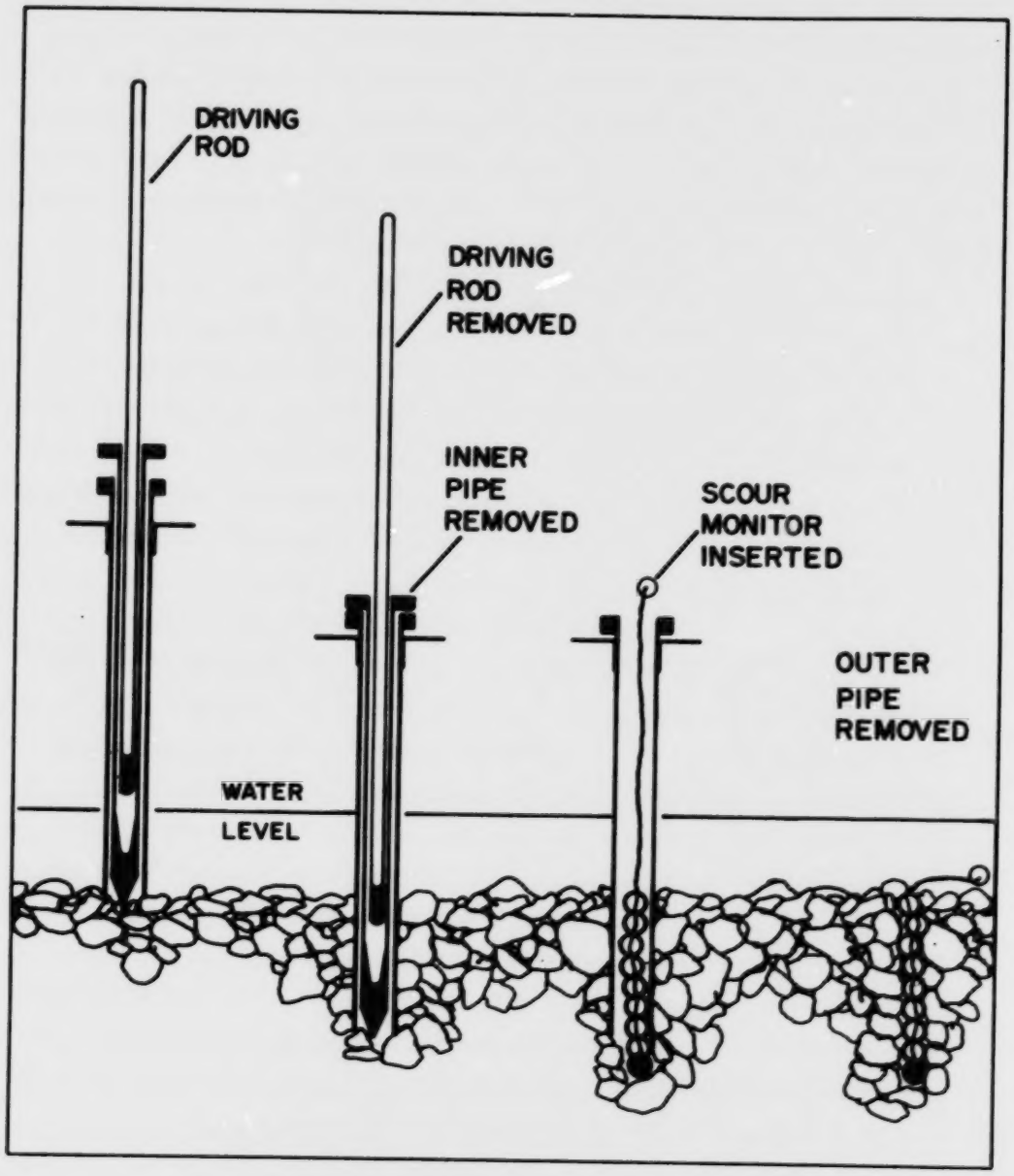

FIGURE 7. Procedure for placing scour monitors into the streambed.

3.5.2 Gravel quality

The quality of spawning gravels impounded by the gabions was examined throughout the post-installation period. Intragravel dissolved oxygen measurements (see Section 3.3) were taken during 1982-83 salmon egg incubation. These were repeated along with permeability measurements (see Section 3.3) in summer 1983. Sampling on the grid systems enabled pairing of stations in treatment and their control sites for t-test analysis. Between 15 and 27 measurements were made at each site.

Gravel composition was analyzed twice after gabion installation as follows: 1) three gravel samples were taken from the surcharged spawning gravels at each of the three treatment sites immediately following gabion installation; and 2) five stations were sampled at all treatment and control sites 1 year after installation (summer 1983) to detect changes in gravel composition attributed to winter stormflows and spawner activity.

Sedimentation is defined in this study as the infiltration and impaction of streambed gravels with fine sediments less than 3 mm. Between 10 and 16 sediment traps were distributed per site at the three treatment sites and at five of the control sites to detect differences in sedimentation rates between treatment and control sites on Sachs Creek. The traps consisted of wide-mouth 1.5-L plastic jars filled with sorted pea gravel larger than 3 mm. The traps were buried flush with the surface, as described by Slaney et al. (1977). The traps collected sediments from December 1982 to March 1983 and were later analyzed by dry sieving. About 60% of the traps were destroyed by scour. Average fine sediment accumulation at the treatment sites were graphically compared to that of control sites.

3.5.3 Streambed configuration

Stream bottom contours of the gabion sites were surveyed with an automatic level (Kern) at several times after installation:

1) immediately following installation, 2) after winter stormflows in February 1983, 3) 1 year after installation in July 1983, and 4) after a second cycle of winter stormflows in February 1984. An additional survey of Treatment Site I was made following major changes in streambed configuration caused by the August 1983 flood.

3.5.4 Spawner use

Two methods of measuring the suitability of treatment sites as salmon spawning habitat were examined: 1) tabulation of salmon spawner activity on all control and treatment sites; and 2) evaluation of habitat suitability based on probability-of-use curves (Bovee and Cochnauer 1977) developed for Sachs Creek pink salmon.

Actual fish usage of the sites was obtained by plotting spawning locations of spawning or redd-defending female salmon. Fish positions usually were mapped every other day throughout the spawning season of 1982 and every other week for the smaller run in fall 1983. A standard form was used in conjunction with the on-site reference grid system to facilitate both plotting fish positions and later analysis. In addition, the portion of the creek used was surveyed every 7-10 days from September to December 1982. Approximate timing of runs, abundance of salmon, and longitudinal distribution of the pink, chum, and coho salmon were recorded.

Probability-of-use curves (Bovee and Cochnauer 1977) were established for pink salmon in October 1982 to determine whether conditions conducive to their spawning were found at gabion sites. These conditions may or may not be related to an intragravel environment required for high egg and alevin survival. Parameters measured on a total of 230 redds included average water depth, water velocity at spawner "nose height" (5 cm above the substrate), and surface substrate composition (a subjective estimate of percent gravels (2 cm$< x <$ 12 cm) and "D50" the diameter at which 50% of the surface particles are smaller or larger). The average

probability-of-use calculated for the treatment sites was compared to that of respective control sites.

3.5.5 Egg survival

Egg survival studies complemented the above studies in two ways: 1) they were designed to detect differences in egg mortality rate between control and treatment sites through paired t-test analysis; and 2) they enabled a correlation of egg survival rates to quality of gravel as measured by intragravel dissolved oxygen, intragravel permeability, gravel quality, and depth of scour.

Egg and alevin densities were sampled with a hydraulic egg sampler (McNeil 1964a). Sampling stations were selected with reference to spawner mapping data; only stations exhibiting a minimum fish usage (2 pink salmon spawner-days) were sampled to minimize sampling areas with no eggs. This criterion precluded sampling sites other than Treatment Site III and its two control sites (IIIA and IIIB), owing to lack of sufficient spawner densities at the other sites. About 20 stations per site were sampled for each sampling period: 1) at the "eyed" stage in December 1982, and 2) immediately prior to pink fry "emergence" from the gravel in March 1983. Sampling consisted of 0.2 m^2 per sample and four adjacent samples per station. The eggs and alevins were extracted to a depth of 40 cm.

Egg sampling for 29 of the December samples was modified to determine the approximate depth that eggs were deposited. These were sampled by inserting the hydraulic probe in the gravel, in increments of 10 cm deep to a maximum of 40 cm. The eggs collected after each increment were analyzed separately. Selection of the 29 depth samples was based on whether an adjacent sample had more than approximately 20 eggs.

Two methods of calculating egg survival (McNeil 1964a) were applied to the egg sampling data. First, the ratio of live to dead eggs sampled was used as a relative measure of survival to date-of-sampling. A second method was developed to eliminate the

bias in survival introduced from natural egg loss. This method required calculation of potential egg deposition from adult fecundities, egg retention, and spawner mapping data. An average spawner longevity of 10 days (McNeil 1964b) was assumed to be necessary for an average deposition (1300 eggs; n=12 "green" Sachs Creek pink salmon females). A paired t-test analysis of survival at individual stations was used to indicate differences in survival rate between Treatment Site III and that of its two control sites (IIIA and IIIB). Stepwise multiple regressions (Rao 1973) were run with egg survival against physical parameters to examine the relationships between the physical environment and egg survival. Intragravel dissolved oxygen and permeability, and depth of gravel scour, measured either during summer 1982 or winter 1982-83, were run against both indices of egg survival at individual sampling stations.

3.5.6 Juvenile use

Juvenile salmonids were enumerated on the gabion and control sites on Sachs Creek in summer 1983 to indicate the effect of gabion installation on salmonid rearing habitat. Juvenile enumeration involved two sampling sessions separated by a 2-3 hour period, which enabled marked fish from the first sampling to return to their original locations prior to the second sampling. Each sampling entailed multiple (two-to-three) passes with both electroshocker (Smith Root, Type VIII) and pole seine (3 m long, 4 mm mesh). Juvenile coho and steelhead were marked by caudal fin-clipping to enable enumeration by the Petersen single census mark-recapture technique. Their fork lengths were measured to detect possible differences in size between the gabion and control sites. Stop nets delineated the study areas during sampling and the re-orientation period. A t-test analysis based on unpaired measurements of individual 0+ coho lengths was made to determine differences in average length between treatment and control sites.

4 RESULTS

4.1 Site Stability

4.1.1 Gravel scour

Gravel scour at two of the gabion sites (I and II) over the first winter (1982-83) was significantly greater ($p < .05$, t-test analysis) than at their respective control sites (Tables 1 and 2). The areas of concentrated gravel scour were generally on the downstream side of the lateral wings of the gabions and in the high velocity channels established by bank deflection (Figure 8). The extent of the bank scour in these corners prompted riprap placement at Treatment Sites II and III where there previously had been none (see 3.4.2, 3.4.3, and 3.4.4). Gravel scour in the second year (1983-84) was not as severe in gabion and control sites as in the first year (1982-83) (Table 1). However, gravel scour at the lower two treatment sites (II and III) decreased more (from 13 cm in the first year to 4.4 cm in the second year) than that of their control sites (IIB, IIIA, and IIIB; from 5.1 cm to 4.5 cm). Scour was therefore similar ($p < .05$; Table 2) in the lower two treatment sites (II and III) and control sites (IIB, IIIA, and IIIB) after the initial stabilization period of one year. Gravel scour at Treatment Site I, at a 3% slope gradient, also decreased in the second year from that in the first year (from an average of 22 cm to 12 cm; Table 1). Scour at Treatment Site I was greater than all other sites in the second year (Table 1), and significantly greater than its control IB (Table 2).

TABLE 1. Depth of gravel scour on study sites at Sachs Creek over winter 1982-83 and 1983-84

Site	Year 1[a]			Year 2		
	No. of stations monitored	Avg. scour (cm)[b]	Std. dev. (Sx)	No. of stations monitored	Avg. scour (cm)	Std. dev. (Sx)
Treatment I	18	22	13	11	12	9.5
Treatment II	17	11	12	19	1.1	2.4
Treatment III	19	15	15	26	6.8	8.2
Totals						
II and III[c]	36	13	13	45	4.4	6.9
I, II and III	54	16	14	56	5.9	8.0
Control IB	12	7.0	11	9	0.9	2.8
Control IIB	16	1.1	2.9	9	0.5	1.4
Control IIIA	15	7.8	8.7	13	5.8	6.3
Control IIIB	N.A.	-	-	11	9.2	9.5
Totals: IB, IIB, IIIA and IIIB	43	5.1	8.4	42	4.5	7.0

[a] Peak stormflow in Year 1 (1982-83) was 1.32 m on staff gauge.
Peak stormflow in Year 2 (1983-84) was 1.14 m on staff gauge.

[b] As indicated by Vertical Erosion Monitors.

[c] These sites are at 1% slope gradient.

TABLE 2. A t-test analysis of gravel scour on study sites at Sachs Creek

Treatment Site (X)	Control site (Y)	Year[a]	Mean Diff.[b] (X-Y)	Std. Dev. of Diff.	t	df	Signif-icance[c]
I	IB	1	2.3	2.6	2.7	9	Sig.
		2	3.8	1.1	9.9	7	Sig.
II	IIB	1	2.4	2.0	4.3	12	Sig.
		2	0.55	1.5	1.1	8	N.S.
III	IIIA	1	0.72	2.5	1.1	14	N.S.
		2	0.23	2.6	0.31	11	N.S.
III	IIIB	2	-0.24	2.7	-0.30	10	N.S.

[a] Monitoring Year 1 from early December 1982 through mid-March 1983; monitoring Year 2 from early September 1983 through late January 1984.

[b] Values of gravel scour (cm) transformed by square root.

[c] $p < .05$; one-tailed paired t-test; Ho: $X \leq Y$; H1: $X > Y$.

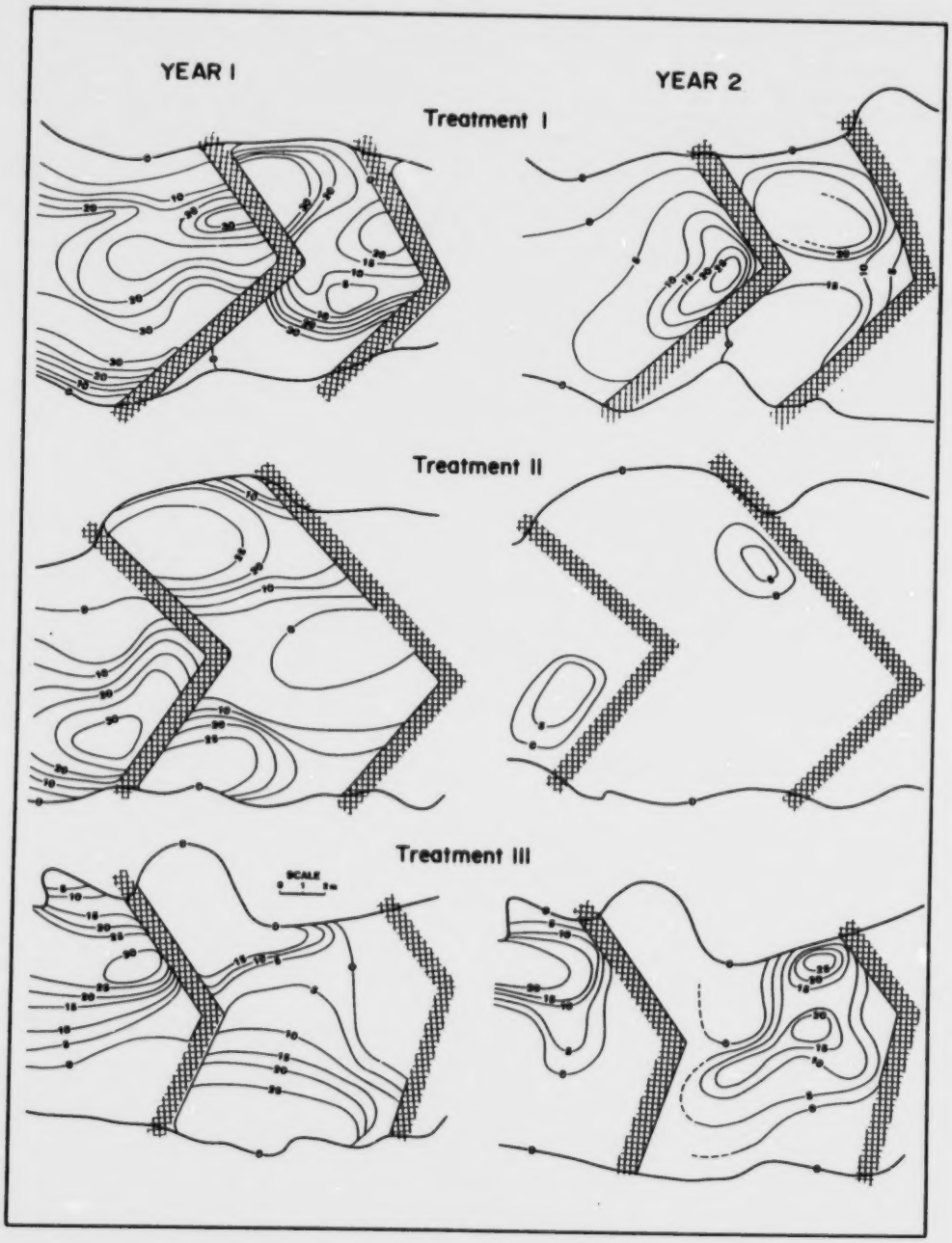

FIGURE 8. Isopleths of gravel scour depth (cm) as indicated by vertical erosion monitors at gabion sites at Sachs Creek in Year 1 and 2.

4.1.2 Gabion site configurations

Configuration of tne gabion sites changed during exposure to their first winter (1982-83) stormflows. Pools about 80 cm deep formed in the downstream lateral corners from gravel scour (Figures 9, 10, and 11). This created two additional pool-riffle sequences per site. Teardrop-shaped gravel bars formed downstream of gabion apices in Treatment Sites II and III. Although the gabions withstood winter stormflows that raised the water surface by 1.1 m, an unseasonal flood on 2 August, 1983, (raising the water surface by 1.2 m) caused Treatment Site I to "fail" (i.e., to change enough to threaten site integrity); approximately 0.5 m of substrate was scoured away for a 30 m reach downstream of the lower gabion (Figure 9). A wedge of streambed sediments with boulders up to 0.7 m diameter inundated the site upstream of the gabions during this flood (Figure 12); this wedge averaged 13 cm thick over a 20 m distance upstream of the gabions. Much of this wedge was scoured away during stormflows in the second year (Figures 9 and 12). Streambed configurations remained relatively constant at the lower two treatment sites (II and III) over the second season of winter stormflows (Figures 10 and 11).

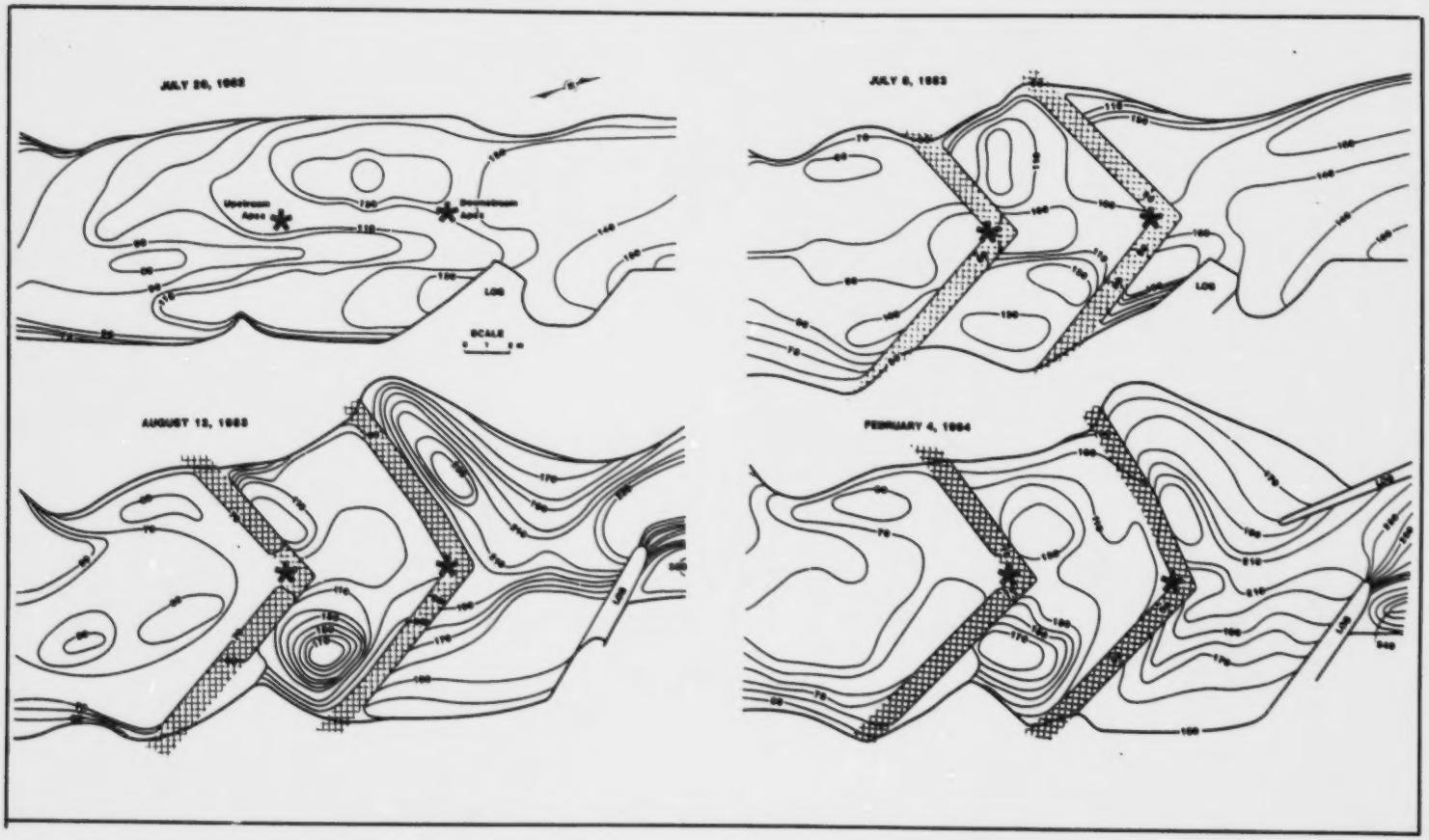

FIGURE 9. Temporal changes in bathymetric contours (cm) below an arbitrary benchmark at Treatment Site I at Sachs Creek.

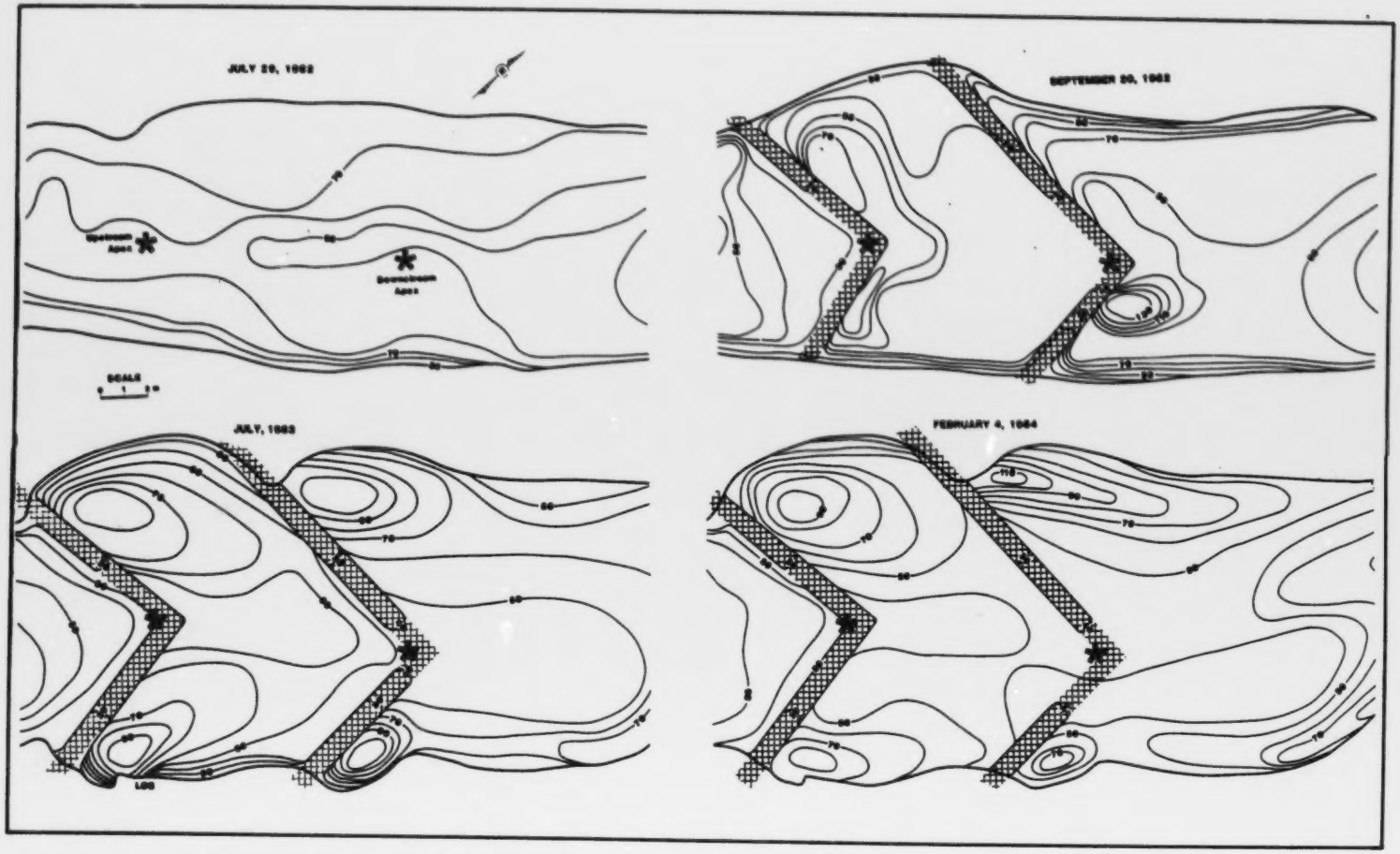

FIGURE 10. Temporal changes in bathymetric contours (cm) below an arbitrary benchmark at Treatment Site II at Sachs Creek.

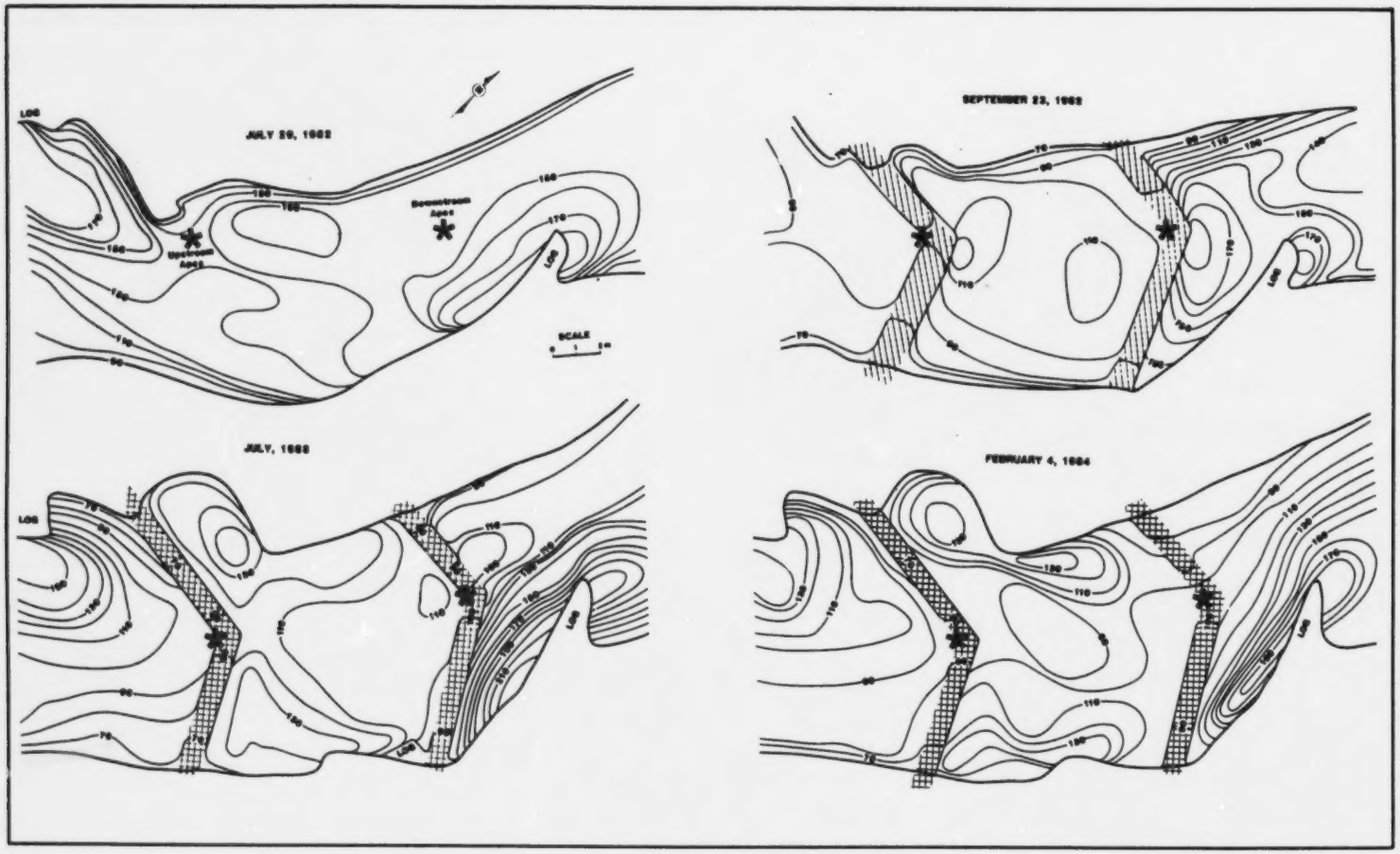

FIGURE 11. Temporal changes in bathymetric contours (cm) below an arbitrary benchmark at Treatment Site III at Sachs Creek.

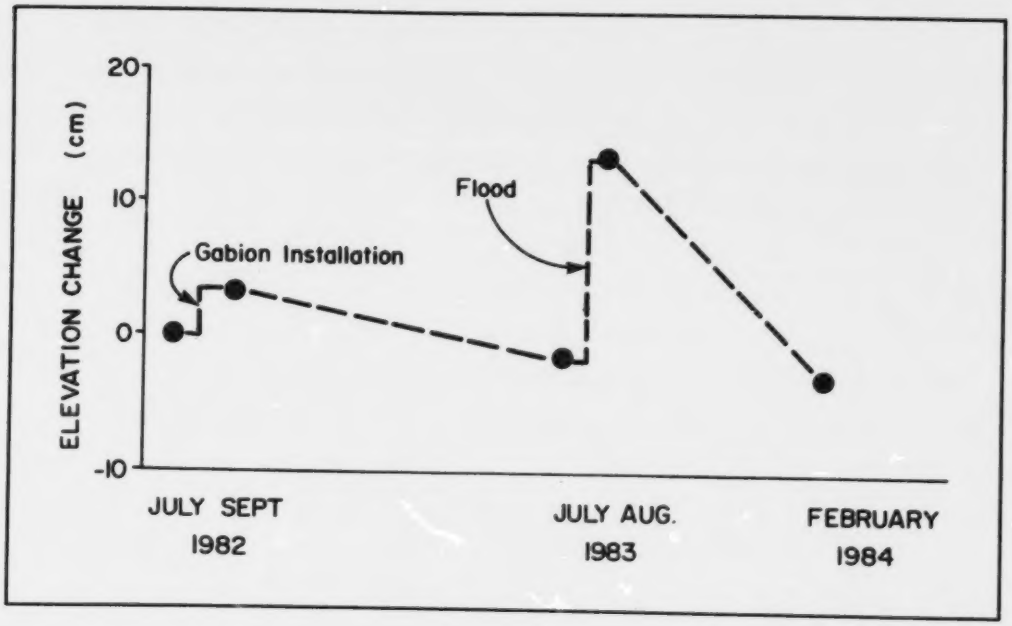

FIGURE 12. Temporal changes in average aggradation above gabions at Treatment Site I, Sachs Creek.

Changes in local streambed slope gradients improved the gravel stabilizing ability of all three gabion sites: the pre-installation three-site average gradient of -1.2% (facing downstream) decreased to an average gradient of +3.1% 1 year after installation (Table 3). (Slope is positive when the bottom of plunge pools are, on average, at a lower elevation than gravels entrapped by gabions further downstream.) The August 1983 flood increased the streambed gradient at Treatment Site I to -1.9%; however, this was still a decrease from the pre-installation gradient of -2.8% (Table 3).

TABLE 3. Summary of streambed gradient changes with gabion installation on Sachs Creek, 1982-83

Treat. Site	Location relative to gabions	Average slope gradient (%) facing downstream		
		Pre-installation[a]	1-Year post-installation[b]	Post-flood Aug. 1983
I	Upstream	-3.0	-1.4	-3.2
	Between	-2.5	+5.0	+3.0
	Downstream	-3.0	+4.0	-5.6
	Average	-2.8	+2.5	-1.9
II	Upstream	-0.2	+4.9	
	Between	-1.1	+3.1	
	Downstream	-1.1	+0.5	
	Average	-0.8	+2.8	
III	Upstream	+1.6	+4.8	
	Between	-1.2	+4.2	
	Downstream	0	+3.3	
	Average	+0.1	+4.1	
Total: I, II and III		-1.2	+3.1	

[a] Surveyed July 1982.
[b] Surveyed July 1983.

4.2 Site Revegetation and Bank Stabilization

Vegetative coverage of mineral soil exposed during gabion construction was more extensive at sites where bank stabilization methods were applied. The site receiving no revegetative attention (Treatment Site I) appeared to have only minimal organic coverage 1.5 years after gabion construction. The site seeded with the grass-legume mix and covered with a seaweed mulch (Treatment Site II) had the highest vegetative coverage at this time. Portions of this site in a lower flood plain remained bare, owing to the seed and seaweed washed away prior to seed germination. Most of the site that was seeded but not fertilized with seaweed (Treatment Site III) had sparse vegetative coverage. The seaweed mulch also appeared to effectively stabilize the steeper machinery access route at Treatment Site II when compared to a similarly seeded but unfertilized access route at Treatment Site III.

Survival of juvenile alders, hemlock, and forbs at Treatment Sites II and III after 1.5 years was approximately 60% (Table 4). Most of these were subjected to flood conditions, suggesting efficient root systems were already developed. Losses of approximately 40% of stock planted were largely through streambank erosion and beaver activity.

4.3 Gravel Quality

4.3.1 Intragravel dissolved oxygen

The effect of gabion installation on intragravel dissolved oxygen was variable between treatments but comparative to controls within treatments (Table 5). Oxygen levels at a combination of all three treatment sites were significantly "improved" when compared to that of the controls; i.e., the intragravel dissolved oxygen at the gabion sites was not significantly different ($p < .05$, paired t-test) from either of their control sites prior to installation but was significantly greater after installation (Table 6). The oxygen levels of Treatment Sites II an III both were significantly improved

TABLE 4. Streambank stocking success on study sites at Sachs Creek, October 1982 to February 1984

Treatment Site	Date	Number of plants				
		Alders		Hemlock	Forbs, etc.	Total
		Alive	Damaged[a]			
II	1982	34		3	2	39
	1984	22	15	3	2[b]	27
III	1982	39		3	9	51
	1984	20	4	1	4	25
II and III	1982	73		6	11	90
	1984	42	19	4	6	52

[a] Trees damaged or destroyed by beaver in winter 1983-84; additional losses resulted from streambank erosion.
[b] Volunteers.

TABLE 5. Summary of intragravel dissolved oxygen and permeability on study sites at Sachs Creek

Site	Sampling period[a]	Dissolved oxygen N	Dissolved oxygen Average (% of srfce)	Dissolved oxygen Std. dev.	Permeability N	Permeability Average (cm/hr)	Permeability Std. dev.
Treat I	Pre	18	88	12	N.A.[b]		
	0.5 Year	20	86	9.6	N.A.		
	1 Year	18	92	8.5	14	2.3×10^3	2.8×10^3
Contr IA	Pre	18	61	32	N.A.		
	0.5 Year	18	85	15	N.A.		
	1 Year	15	96	4.7	N.A.		
Contr IB	Pre	20	24	26	N.A.		
	0.5 Year	18	64	31	N.A.		
	1 Year	20	43	32	14	3.8×10^3	2.7×10^3
Treat II	Pre	19	30	27	15	3.1×10^2	3.0×10^2
	0.5 Year	23	80	22	N.A.		
	1 Year	23	65	28	17	1.7×10^3	2.5×10^3
Contr IIA	Pre	18	54	28	18	2.8×10^2	4.0×10^2
	0.5	23	58	25	N.A.		
	1 Year	21	45	28	17	6.0×10^2	1.1×10^3
Contr IIB	Pre	20	43	33	21	6.5×10^2	7.0×10^2
	0.5 Year	23	49	28	N.A.		
	1 Year	23	33	25	20	6.0×10^2	6.9×10^2
Treat III	Pre	19	13	17	16	1.4×10^3	6.1×10^2
	0.5	25	72	22	N.A.		
	1 Year	18	74	18	18	3.1×10^3	2.8×10^3
Contr IIIA	Pre	21	60	31	21	8.2×10^2	1.1×10^3
	0.5 Year	26	46	31	N.A.		
	1 Year	19	44	26	20	2.5×10^3	2.1×10^3
Contr IIIB	Pre	18	58	29	19	1.1×10^3	1.7×10^3
	0.5 Year	27	55	25	N.A.		
	1 Year	19	47	28	17	2.4×10^3	2.4×10^3

TABLE 5. Continued

Site	Sampling period[a]	Dissolved oxygen N	Dissolved oxygen Average (% of srfce)	Dissolved oxygen Std. dev.	Permeability N	Permeability Average (cm/hr)	Permeability Std. dev.
Totals:							
Treat[c] I, II and III	Pre	56	43	38	31	8.7×10^2	7.3×10^2
	0.5 Year	68	79	20	N.A.		
	1 Year	59	76	23	49	2.4×10^3	2.7×10^3
Contr[c] IA, IIA and IIIA	Pre	57	58	30	39	5.7×10^2	8.7×10^2
	0.5 Year	67	60	30	N.A.		
	1 Year	55	58	33	37	1.6×10^3	2.0×10^3
Contr[c] IB, IIB and IIIB	Pre	58	41	32	40	8.6×10^2	1.3×10^3
	0.5 Year	68	55	29	N.A.		
	1 Year	62	41	29	37	1.4×10^3	1.9×10^3

[a] Pre-installation sampling in July and August 1982; 0.5-year post-installation sampling in February and March 1983; 1-year post-installation sampling in July and August 1983.
[b] N.A. = Not Available.
[c] Totals for permeability included Treatments II and III, and Controls IIA, IIIA, IIB, and IIIB only.

TABLE 6. A t-test analysis of intragravel dissolved oxygen on study sites at Sachs Creek

Treat. Site (X)	Control site (Y)	Sample date[a]	Mean diff.[b] (X-Y)	Std. dev. of diff.	t	df	Signif-icance[c]
I	IA (Marginal habitat)	Pre	20	26	2.8	13	Sig.
		0.5 Year	1.1	16	0.3	17	N.S.
		1 Year	-1.6	6.1	-0.96	12	N.S.
I	IB (Prime habitat)	Pre	61	27	8.9	15	Sig.
		0.5 Year	22	30	3.1	17	Sig.
		1 Year	49	35	6.0	17	Sig.
II	IIA (Marginal habitat)	Pre	-27	41	-2.6	15	N.S.
		0.5 Year	22	30	3.5	22	Sig.
		1 Year	21	46	2.1	20	Sig.
II	IIB (Prime habitat)	Pre	-14	45	-1.4	18	N.S.
		0.5 Year	31	36	4.1	22	Sig.
		1 Year	32	43	3.4	21	Sig.
III	IIIA (Marginal habitat)	Pre	-55	28	-8.3	17	N.S.
		0.5 Year	22	38	2.9	24	Sig.
		1 Year	29	30	4.1	17	Sig.
III	IIIB (Prime habitat)	Pre	-45	27	-7.1	17	N.S.
		0.5 Year	15	27	2.8	25	Sig.
		1 Year	24	31	3.3	17	Sig.
Totals:							
I, II, and III	IA, IIA, IIIA (Marginal habitat)	Pre	-24	44	-3.7	47	N.S.
		0.5 Year	17	31	4.3	64	Sig.
		1 Year	18	36	3.6	50	Sig.
I, II, and III	IB, IIB, IIIB (Prime habitat)	Pre	-2.3	55	-0.3	52	N.S.
		0.5 Year	23	31	5.8	65	Sig.
		1 Year	35	38	7.0	57	Sig.

[a] Pre-installation sampling in July and August 1982; 0.5-year post-installation sampling in February and March 1983; 1-year post-installation sampling in August 1983.

[b] Intragravel oxygen values were expressed as percent of dissolved oxygen of surface water.

[c] $p < .05$; one-tailed paired t-test; Ho: $X \leq Y$; H1: $X > Y$.

after gabion installation. The oxygen levels of Treatment Site I decreased after gabion installation when compared to that of its control sites; the average dissolved oxygen concentration at this gabion site was significantly greater than Control Site IA prior to installation, but was not different after installation (Table 6). The intragravel dissolved oxygen at Treatment Site I remained significantly greater than Control Site IB before and after installation (Table 6).

4.3.2 Intragravel permeability

The effect of gabion installation on intragravel permeability also varied considerably between the sites (Table 5). Permeability of gravels at a combination of Treatment Sites II and III were significantly ($p < .05$) improved relative to Control Sites IIB and IIIB, and maintained a significantly greater permeability than that at Control Sites IIA and IIIA (Table 7). The permeability of Treatment Site II significantly increased following gabion installation ($p < .05$; Table 7). The permeability of Treatment Site III also increased after gabion installation (Table 5). However, the permeability at the gabion site was significantly greater than that at its two control sites prior to gabion installation, whereas it was not significantly greater after installation (Table 7). This was probably owing to a three-fold increase in the variability of permeability at Treatment Site III (standard deviation; Table 5). At Treatment Site I, the stream substrate was too coarse for permeability measurements prior to gabion installation; and the post-installation measurements indicated that its permeability also was not significantly greater than Control Site IB (Table 7). Stream substrate of Control Site IA remained too coarse for permeability measurements at both sampling periods.

TABLE 7. A t-test analysis of intragravel permeability on study sites at Sachs Creek

Treat. Site (X)	Control site (Y)	Sample date[a]	Mean diff.[b] (X-Y)	Std. dev. of diff.	t	df	Signif-icance[c]
I	IB (Prime habitat)	Pre	-8.1	25	-1.3	14	N.S.
II	IIA (Marginal habitat)	Pre	1.2	3.2	1.4	13	N.S.
		1 Year	15	21	3.2	20	Sig.
II	IIB (Prime habitat)	Pre	-4.5	9.3	-1.9	14	N.S.
		1 Year	15	21	3.3	20	Sig.
III	IIIA (Marginal habitat)	Pre	5.2	10	2.0	14	Sig.
		1 Year	-0.18	20	-0.04	20	N.S.
III	IIIB (Prime habitat)	Pre	5.8	11	2.1	15	Sig.
		1 Year	7.5	18	1.7	17	N.S.
Totals:							
II, and III	IIA and IIIA (Marginal habitat)	Pre	3.3	7.7	2.3	28	Sig.
		1 Year	7.3	22	2.2	41	Sig.
II, and III	IIB and IIIB (Prime habitat)	Pre	0.87	11	0.42	30	N.S.
		1 Year	11	20	3.6	38	Sig.

[a] Pre-installation sampling in July and August 1982; 1-year post-installation sampling in June and July 1983.

[b] Intragravel permeability values expressed as mL/sec entering the standpipe, before conversion to cm/hr (Terhune 1958).

[c] $p < .05$; one-tailed paired t-test; Ho: $X \leq Y$; H1: $X > Y$.

4.3.3 Gravel composition

The composition of gravels on the Treatment Sites in Sachs Creek changed with the addition of gravels from a quarry and again with a cycle of spawning and winter stormflows. At Treatment Site I (3% streambed slope gradient) the most notable changes were found with gravels between 10 mm and 70 mm diameter, the suitable range for pink and chum salmon spawning. The proportion of these gravel sizes increased with the addition of quarry gravels, but were reduced to almost the low proportions found before installation following the flushing effect of winter stormflows (Figure 13). Gravels 20-60 mm in diameter at Treatment Sites II and III (at a 1% streambed slope gradient) appeared more abundant 1 year after installation than those before installation (Figure 13).

The amount of fine sediments in the gravel entrapped by gabions and measured by gravel sample sieving varied between the sites. The "fines" in Treatment Site III decreased more than 50% between pre-gabion installation to 1-year post-installation (Figure 14); this reduced the fines to levels below those in both of its control sites (IIIA and IIIB). Changes in fines at Treatment Site II were minor, with levels remaining slightly below its control sites (IIA and IIB; Figure 14). Only a minor flushing of fines from the added quarry gravels was evident at Treatment Site I (Figure 14); the coarse nature of the substrate prior to installation prevented pre- and post-installation comparison of the finer component of the gravels at this site.

4.3.4 Sedimentation

The loss of most of the sediment traps through winter stormflows (all in the case of Treatment Site I) precluded statistical analysis of results. Fine sediment (less than 3 mm) accumulation in traps at Treatment Site II was 40-50% lower than that of its two control sites (IIA and IIB; Figure 15). Fine sediment accumulation at Treatment Site III ranged from 10-70% higher than that of its two control sites (IIIA and IIIB; Figure 15).

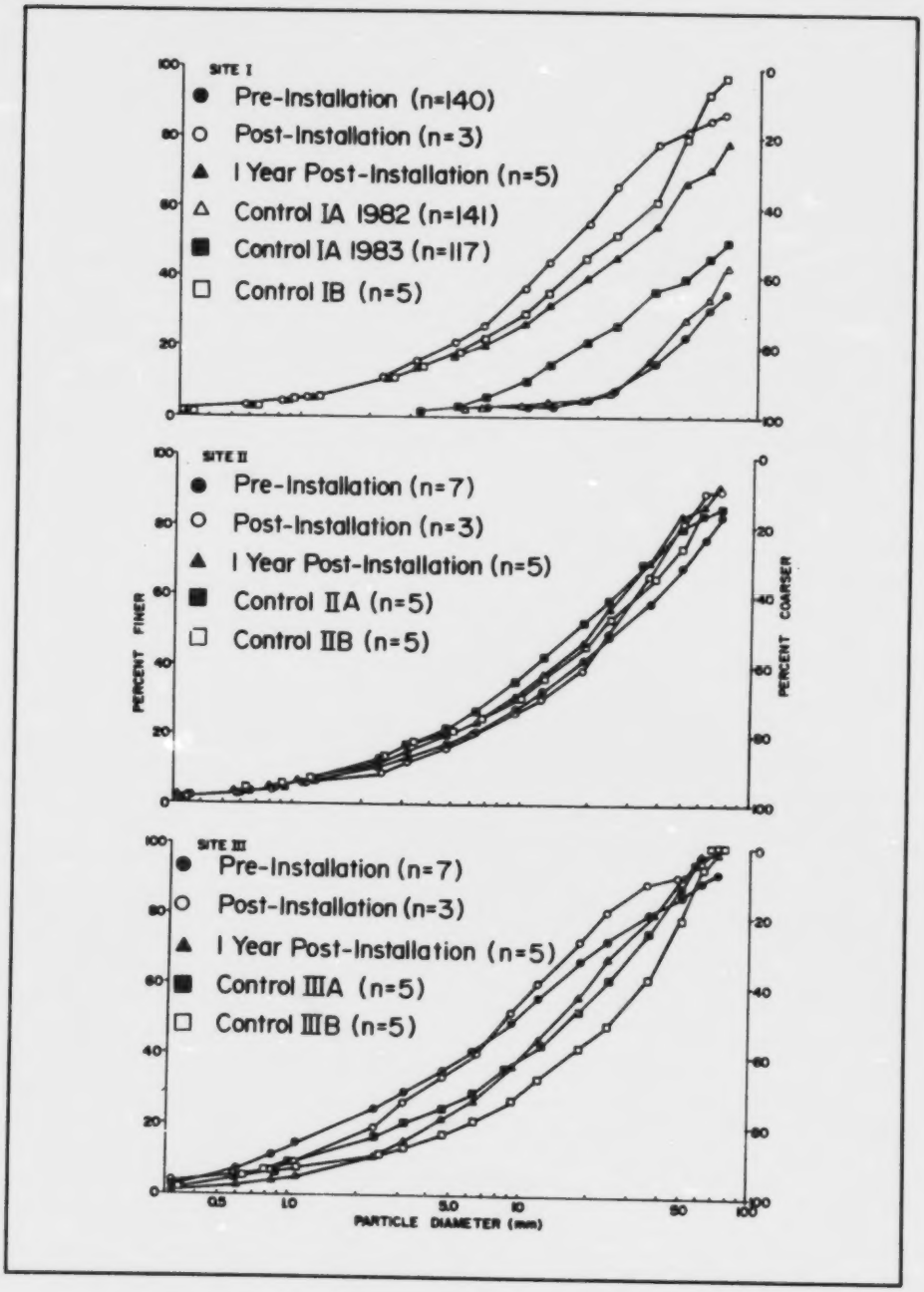

FIGURE 13. Gravel composition of study sites at Sachs Creek pre- and post-gabion installation.

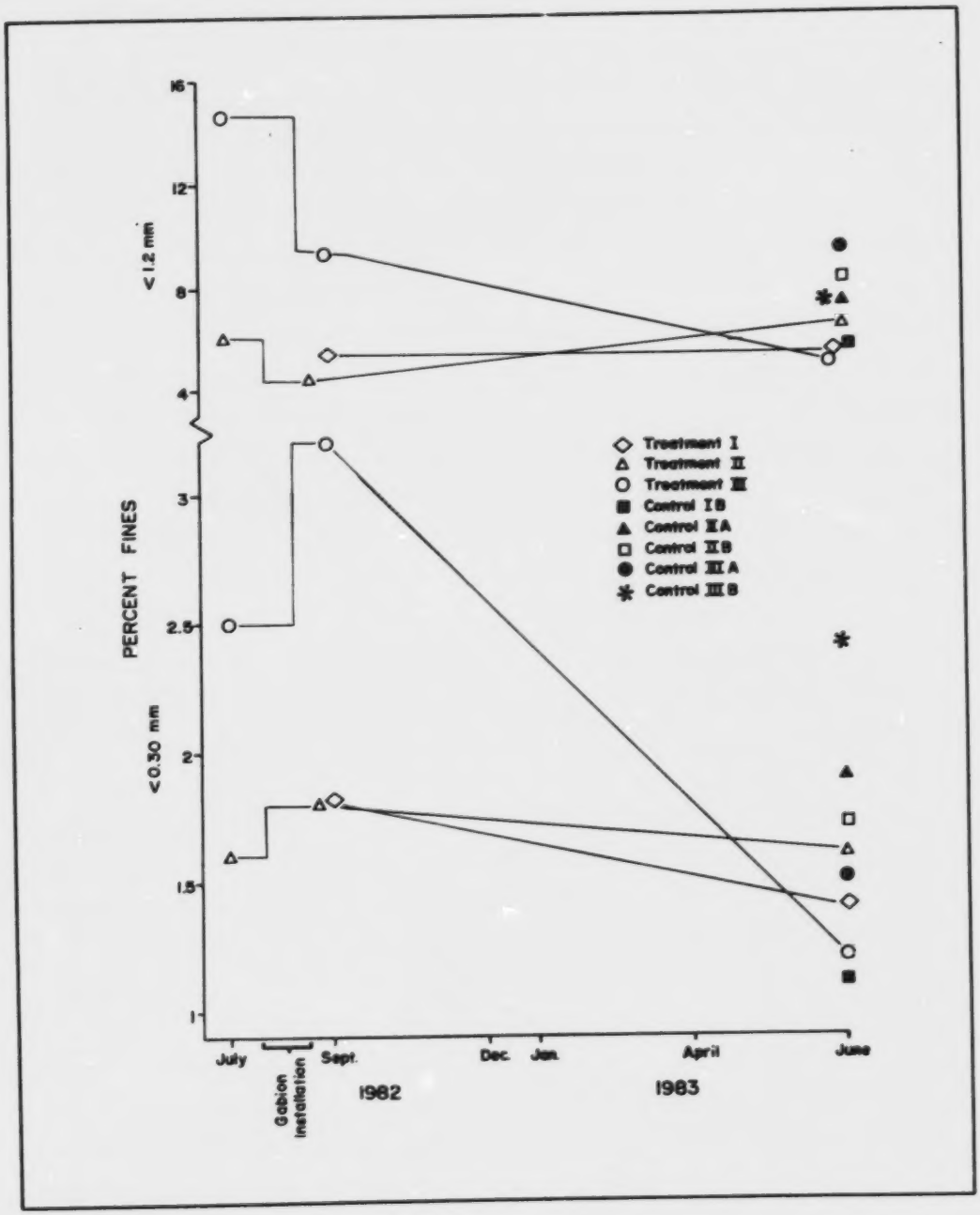

FIGURE 14. Mean percent of particles less than 1.2 and 0.30 mm on study sites at Sachs Creek.

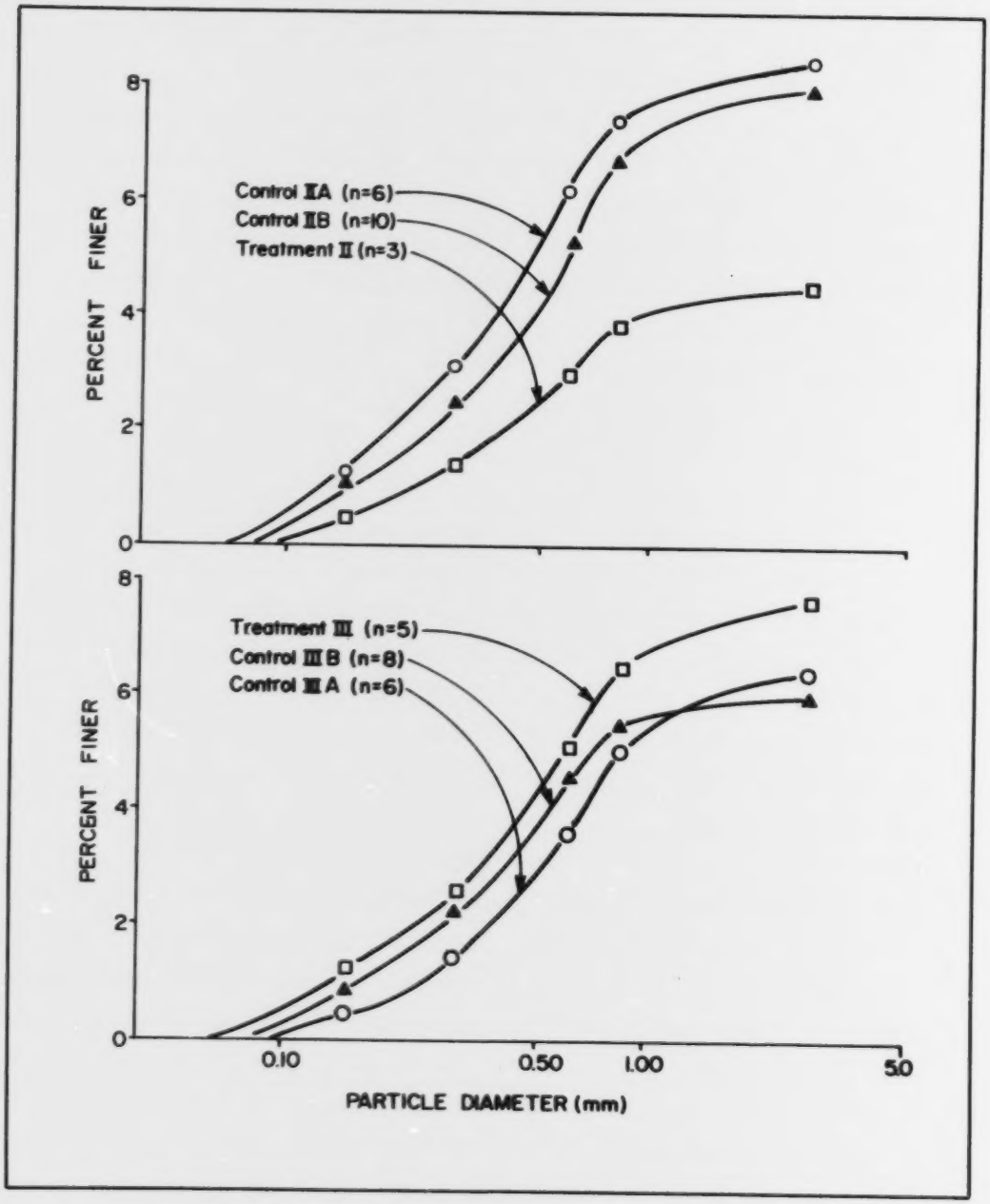

FIGURE 15. Sedimentation accumulated in sediment traps on study sites at Sachs Creek, December 1982 to March 1983.

Different sizes of "fines" may vary in severity of effects on egg survival. It was not until the particle size examined in another study was reduced to less than 0.03 mm diameter that a significant negative correlation was found between amount of fines and egg-to-fry survival (Slaney et al. 1977). Fines less than 0.30 mm diameter were analyzed in both sieved gravel samples (Figure 14) and sediment accumulation (Figure 15). The effects of gabions on the amount of fines less than 0.30 mm diameter was similar to that discussed above for fines less than 1.2 mm diameter (Figure 14) and for fines less than 3.0 mm diameter (Figure 15).

4.4 Spawner Use

4.4.1 Observed spawning

Longitudinal distribution of pink and chum spawners in 1982 (Figure 16) indicated that the gabion locations were upstream of the main concentration of spawners, with Treatment Site I beyond the upstream limits of pink and chum spawning. Fewer salmon were observed spawning in 1983 than in 1982, because 1983 was an "off year" for pink salmon runs and sites were monitored only approximately 10% as often as in 1982 (Table 8). Spawner observations in 1983 were insufficient for site comparison. The 1982 coho spawner usage of Treatment Site I was greater than that in its controls (IA and IB; Table 8). Treatment Site II had more spawning activity than did its (marginal habitat) Control Site IIA but less than its (prime habitat) Control Site IIB. Treatment Site III had less spawning activity than either of its two control sites (IIIA and IIIB; Table 8). The effect of the longitudinal distribution of spawners on site usage is discussed further in 5.2.2.

The sequence of spawning at Sachs Creek was first chum, then pink, and finally coho salmon. However, temporal distribution of the majority of the pink spawning overlapped with the chum and coho. Chum spawning rarely overlapped with coho. Gradual spawner migration

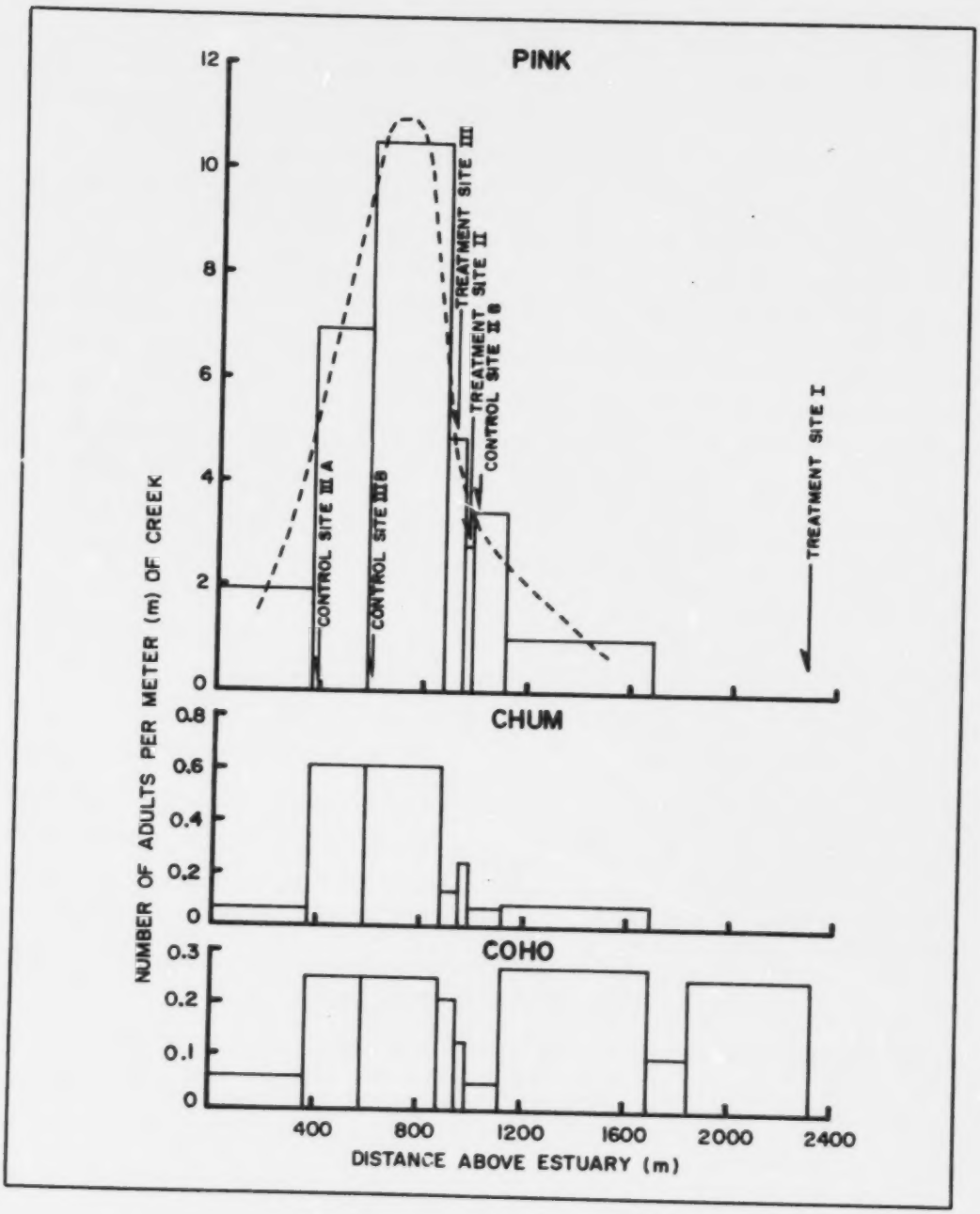

FIGURE 16. Longitudinal distribution of adult salmon in Sachs Creek, September to November 1982.

TABLE 8. Distribution of salmon spawning activity on study sites at Sachs Creek, fall 1982 and 1983

Site	Spawning habitat quality	Distance above estuary (m)	Sum of female salmon activity[a]								Avg. 1982 density[b] pink (No./m^2)
			1982				1983				
			Pink	Chum	Coho	Σ	Pink	Chum	Coho	Σ	
Treatment I		2285	0	0	18	18	0	0	1	1	0
Control IA	Marginal	2185	0	0	0	0	0	0	1	1	0
Control IB	Prime	1820	0	0	14	14	0	0	0	0	0
Treatment II		935	138	5	7	150	1	2	0	3	0.072
Control IIA	Marginal	1100	99	0	7	106	0	0	0	0	0.079
Control IIB	Prime	985	342	3	12	357	0	0	0	0	0.27
Treatment III		875	445	27	0	472	0	0	0	0	0.30
Control IIIA	Marginal	360	676	67	14	757	2	4	0	6	0.53
Control IIIB	Prime	575	894	186	20	1,100	5	5	0	10	0.71

[a] 1982 values were the total numbers of observations of female salmon spawning or redd-defending. Values were the totals of 53 observation days with intervals averaging 1.5 days. Individual spawners remaining on the site were counted several times (ca. six) on different days. 1983 values were the sums over six observation days (1-2 week intervals); additional fish spawned on the sites, as evidenced by their redds.

[b] Pink salmon density calculations were based on 42 observation days within a temporal range of 62 days of pink presence on the sites. Therefore, each observation represented an average of 1.5 spawner days. Since pink spawners remain on a site an average of 10 days (McNeil 1964b), each observation represents 0.15 spawners.

up the stream was evident as the lowest sites (Controls IIIA and IIIB) exhibited spawning about 10 days prior to Treatment Sites II and III further upstream.

4.4.2 Probability-of-use

Treatment Site II showed the greatest suitability of spawning habitat in comparison to that of its marginal habitat control (IIA) -- a difference of 440% (Table 9). Treatment Site III showed greater suitability than its prime habitat control (IIIB) -- a difference of 13% -- but less than its "marginal habitat" control (IIIA). Probability-of-use measurements were made after Treatment Site I had "failed" during the August 1983 flood (see Section 5, Discussion). Treatment Site I showed poorer pink spawning habitat than either of its controls (IA and IB).

4.5 Egg Survival

Pink salmon egg survivals measured in March were lower than in December, particularly in the control sites (Table 10). The difference in survival was probably the result of some pink fry emergence from the gravels between the two sampling periods. Fry emergence prior to March sampling was supported by Accumulated Thermal Unit (ATU)[4] calculations. Salmonid embryo development was proportional to water temperature; between 250 and 400 ATU's were required for the development of pink alevins from hatching to emergence (G. Taccogna, personal communication).[5] It was assumed that pink hatching began about December 1, as 3% of the pink embryos sampled between December 3 and 8 in this study were recently hatched.

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[4] One ATU = one degree C day; e.g. an average temperature for 1 day of 5°C yields an ATU value = 5. ATU's were approximated by the noon temperatures, as recorded in Sachs Creek by a calibrated Ryan/Peabody continuous recording thermograph.

[5] G. Tacconga, Community Advisor, Salmonid Enhancement Program, Dept. Fisheries and Oceans, Queen Charlotte City, B.C.

TABLE 9. Summary of probability-of-use by spawning pink salmon on study sites at Sachs Creek, 1-Year post gabion installation

Site	Habitat quality	Distance above estuary (m)	Stations sampled (N)	Average probability[a]
Treatment I		2285	33	0.014
Control IA	Marginal	2185	20	0.052
Control IB	Prime	1820	20	0.051
Treatment II		935	38	0.052
Control IIA	Marginal	1100	38	0.012
Control IIB	Prime	985	40	0.15
Treatment III		875	34	0.11
Control IIIA	Marginal	360	31	0.15
Control IIIB	Prime	575	40	0.091

[a] Average probability-of-use was the average of the product of the probabilities of four variables measured at each station where their values were determined from probability-of-use curves (Appendix 1). The probability-of-use curves described by Bovee and Cochnauer (1977) and established for pink salmon in Sachs Creek (Appendix 1) are indices of "suitability" rather than actual "probability". This is owing to a value derived from a curve is not one of a group of weights whose collective sum equals a probability of one.

TABLE 10. Summary of egg survival on study sites at Sachs Creek, fall and winter 1982-83

Site	Sampling period	N	Potential survival[a] Average survival (%)	Potential survival[a] Std. dev.	Relative survival[b] Average survival (%)	Relative survival[b] Std. dev.
Treatment III	Dec.	20	11	10	95	38
	March	15	4.3	19	89	37
Control IIIA	Dec.	20	11	15	71	36
	March	17	1.0	4.1	16	22
Control IIIB	Dec.	20	7.9	14	68	27
	March	19	1.6	3.7	39	34

[a] Survival to date of pink salmon eggs and alevins from potential egg deposition.

[b] Relative survival of pink, chum and coho salmon =

$$\frac{\Sigma \text{live eggs and alevins}}{\Sigma \text{ live} + \Sigma \text{dead}} \times 100\%$$

Between hatching and the embryo sampling period in March, the ATU value exceeded 300 (Figure 17), suggesting pink emergence was underway prior to March sampling. The ATU value may have been considerably higher in the intragravel water than that recorded in the surface; studies in Carnation Creek indicated that at some locations, subsurface temperatures may be 2.5°C higher than surface water during much of the winter period, with local measurements as much as 5.9°C greater (Hartman and Leahy 1983).

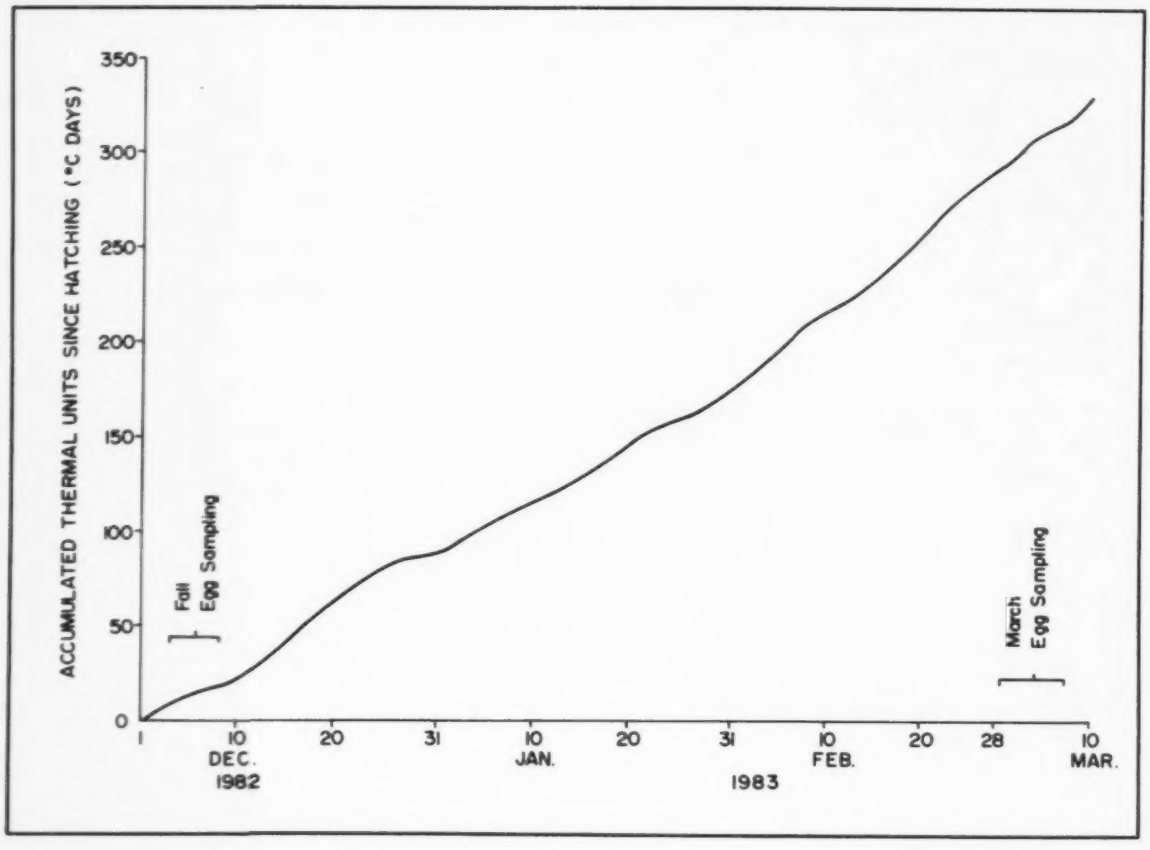

FIGURE 17. Accumulated thermal units at Sachs Creek over fall and winter 1982-1983.

Another factor that influenced the March survival values was the timing of egg deposition. Pink salmon spawning began 10 days later on Treatment Site III than at its control sites (IIIA and IIIB); a corresponding later emergence may account for some of the higher survival values found there in March (Table 10). The probable fry emergence from the gravel prior to the March sampling precluded its further analysis; only the egg survival to December was included in later discussion.

Average egg survival appeared to be greater at Treatment Site III than at its two controls (Table 10), but paired t-test analysis indicated that this difference was not significant ($p < .05$) for either the relative or the potential survival index (Table 11). An "egg capacity" for pink salmon spawning areas was established from an optimum spawner density of one female pink per square metre (McNeil 1964b). Egg capacity was exceeded in all three sites sampled, with a proportion of potential deposition in excess of egg capacity in the stations sampled ranging from 10% for Treatment Site III to 30% for both of its controls (IIIA and IIIB; Table 12). Egg survival at individual stations was examined in a stepwise multiple regression analysis (Rao 1973) to detect correlations with intragravel dissolved oxygen, intragravel permeability, and depth of gravel scour. Although no significant ($p < .05$) multiple regressions were found, three simple correlations were indicated. Significant correlations ($p < .05$) were found between the index of relative egg survival and three different groups of intragravel dissolved oxygen measurements: 1) at Treatment Site III in February 1983 (correlation coefficient $r=0.54$; D.F.=18); 2) at Control Site IIIA in August 1982 ($r=0.48$; D.F.=18); and 3) at a combination of Treatment Site III and Control Site IIIB in February 1983 ($r=0.41$; D.F.=37).

During sampling, eggs were frequently encountered within 10 cm of the gravel surface. On further examination of 29 depth samples, approximately one-half of the pink eggs were deposited within reach of the hydraulic probe when inserted in the surface 20 cm of gravel, and the other half when inserted betwen 20 cm and 40 cm (Table 13).

TABLE 11. A t-test analysis of egg survival in Year 1 on Treatment Site III and its controls at Sachs Creek

Treatment Site (X)	Control site (Y)	Type of survival[a]	Mean diff. (X-Y)	Std. dev.	t	df	Signif-icance[b]
III	IIIA	Potential	-3.6	18	-0.87	18	N.S.
		Relative	0.16	0.50	1.4	18	N.S.
III	IIIB	Potential	1.0	12	0.37	18	N.S.
		Relative	0.14	0.36	1.7	18	N.S.

[a] Survival from time of deposition to the "eyed" stage in December 1982 was expressed by two indices:

i) Potential survival equals:

$$\frac{\text{(Number of live pink eggs sampled)}}{\text{(Potential number of pink eggs deposited)}} \times 100\%$$

ii) Relative survival equals:

$$\frac{(\Sigma \text{ live pink, chum and coho sampled})}{(\Sigma \text{ live}) + (\Sigma \text{ dead eggs sampled})} \times 100\%$$

[b] $p < .05$; one-tailed paired t-test; Ho: $X \leq Y$; Hl: $X > Y$.

[t (at $p < .05$ for df=18) = 1.73]

TABLE 12. Redd superimposition on egg-sampling stations at Sachs Creek, 1982

Site	Stations with redd superimposition[a]			Percent of potential pink egg deposition in excess of pink egg capacity[d]
	By pinks only[b]	By chum and coho[c]	By all species	
Treatment III	4	0	4	10
Control IIIA	10	2	12	30
Control IIIB	13	8	16	30

[a] 19 stations were sampled for egg densities at each of Treatment Site III and its controls.
[b] Where pink densities exceeded one female per square metre, calculated from one redd=10 female spawner days observed.
[c] Where chum or coho spawned over previous pink salmon redds.
[d] Assuming an optimum egg capacity of one female pink per square metre (McNeil 1964b). Effect of superimposition by other species was not included.

TABLE 13. Vertical distribution of pink salmon eggs at Sachs Creek, December 1982

Egg depth[a] (cm)	Live pink eggs[b]		Dead eggs	
	Number	Percent	Number	Percent
0 - 10	387	31	164	38
10 - 20	313	25	159	37
20 - 30	279	22	37	9
30 - 40	280	22	67	16
Total 0 - 40	1259	100	427	100

[a] This was the depth to which the hydraulic probe was inserted. It was assumed that eggs from below this depth were not drawn to the surface by the bubbling action of the probe. Eggs below 40 cm were not sampled.
[b] N = 19 stations.

4.6 Juvenile Use

Coho salmon and rainbow trout were the predominant juvenile salmonids occurring throughout summer on the study sites in Sachs Creek. Pink and chum salmon fry migrated to sea soon after emergence from the gravel in early spring. Before the August 1983 flood, the densities of juvenile coho and rainbow trout were 69-92% higher in the gabion sites than in their respective control sites (Table 14). After this flood, the densities of juveniles were 91-224% higher in the gabion sites than in their respective control sites (Table 14). The August 1983 flood reduced these populations between 20 and 80% (Table 14). Many of the juveniles (16-77%) marked prior to the flood were present at the same site afterwards (Table 15). Gabions did not appear to have any consistent effect on survival rate of marked juveniles during the flood event (Table 15). The coho lengths most frequently encountered were identical for all gabion and control sites in the lower 2 km of Sachs Creek (Figure 18). Larger coho were more abundant than smaller ones (significant at $p < .05$) in the higher slope gradient sites (Treatment Site I and Control IA; Table 16 and Figure 18).

TABLE 14. Juvenile salmonid usage of study sites on Sachs Creek, pre- and post-flood, summer 1983

Site type	Location relative to gabions	Pre-flood (July)			Post-flood (August)		
		No. of sites	Avg. density[a]		No. of sites	Avg. density	
			Coho	Coho+Rb[b]		Coho	Coho+Rb
Treatment:							
	Upstream	3	1.7		1	0.54	
	Between	3	1.0		2	0.43	
	Downstream	2	1.3		2	0.96	
	Total[c]	3	1.2	1.6	2	0.67	1.1
					3[d]	0.53	0.89
Control A's (marginal habitat)		2	0.59	0.82	2	0.16	0.33
Control B's (prime habitat)		3	0.82	0.93	2	0.34	0.56
All Controls		5	0.73	0.89	4	0.25	0.45

[a] Density in fish per square metre.
[b] Rb = Rainbow Trout = Steelhead.
[c] Data from above categories were totalled to calculate overall densities at the sites.
[d] This total includes the densities of Treatment Site I, heavily damaged by the 2 August, 1983, flood.

TABLE 15. Juvenile salmonid population dynamics through the 2 August, 1983, flood at Sachs Creek

Site type	Location relative to gabions	Change in population density			Recurrence of marked pre-flood fish[a]		
		Coho	Rb[b]	Total	Coho	Rainbow	Total
Treatments II and III Combined:							
	Upstream	-53%			16%		
	Between	-61%			55%		
	Downstream	-26%			31%		
	Total	-51%	+26%	-36%	36%	77%	42%
Controls IIA & IIIA (marginal habitat)		-84%	?[c]	-70%	59%[d]	?	43%
Controls IIB & IIIB (prime habitat)		-21%	?	-19%	27%	?	21%
Treatment I[e]		-92%	-34%	-76%	?	46%	33%

a Values approximate the proportion of fish found on a site before the flood that are found on the same site after the flood, where recurrence =

$$\frac{\text{(proportion of marks in pop. post-flood)}}{\text{(proportion of pop. marked pre-flood)}} \times 100\%$$

b N.B. recruitment of 0+ rainbows hatched in late spring was included in post- but not pre-flood population estimates.

c Sample size was insufficient to calculate the population. When trout data were added to coho data, a total was possible.

d A recurrence of 59% of the coho at the Control Sites IIA and IIIA was in conflict with the estimated 84% reduction in coho population at these sites. This may be from effects of sampling small populations after the flood (about 14 and 42 respectively).

e Treatment Site I was separated, owing to extensive damage at this high energy site.

TABLE 16. A t-test analysis of juvenile coho length frequencies on study sites at Sachs Creek, summer 1983

X	N	Mean length (mm)	Y	N	Mean length (mm)	t[a]	df	Signif-icance[b]
Treat I	62	56	Contr IA	48	50	4.6	108	Sig.
Treat I	62	56	Contr IB	66	44	11	126	Sig.
Contr IA	48	50	Contr IB	66	44	4.8	112	Sig.
Treat I	62	56	Treat II	41	47	7.3	101	Sig.
Treat I	62	56	Treat III	99	47	8.1	159	Sig.
Treat II	41	47	Contr IIA	40	43	2.0	79	Sig.
Treat II	41	47	Contr IIB	49	46	0.88	88	N.S.
Treat III	99	47	Contr IIIA	26	46	0.31	123	N.S.
Treat III	99	47	Contr IIIB	26	47	-0.33	123	N.S.

[a] Calculations of t based on unpaired observations of individual 0+ coho salmon lengths.
[b] $p < .05$; one-tailed t-test; Ho: $X \leq Y$; H1: $X > Y$.

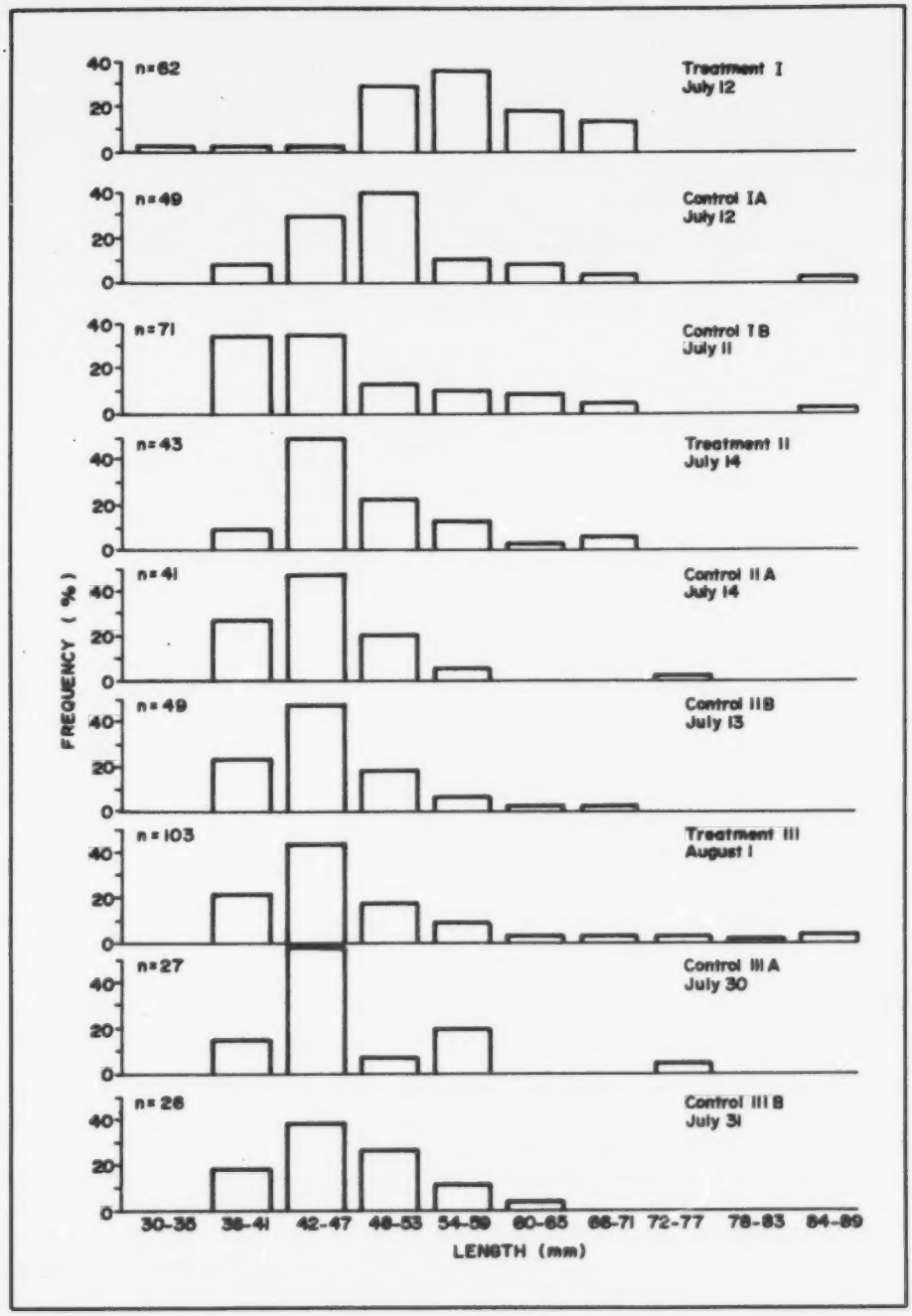

FIGURE 18. Juvenile coho length frequencies on study sites at Sachs Creek, pre-flood, summer 1983.

5 DISCUSSION

To be successful for stream rehabilitation, gabion weirs should:

i. create streambed configurations conducive to adult salmonid spawning;
ii. trap gravel that is not subjected to excessive scour and aggradation action of stormflows;
iii. trap gravel that has a quality conducive to high egg-to-fry survival;
iv. provide a pool-riffle configuration suitable for rearing juvenile salmonids (coho and steelhead);
v. exhibit an acceptable benefit/cost effectiveness.

The following discussion considers the effectiveness of gabion weirs in Sachs Creek in meeting the above criteria.

Benefits of gabion installation in streams devastated by debris torrents may be more pronounced than in many streams with naturally suitable spawning habitat. In Sachs Creek, the uppermost gabion site (I) was in a region severely affected by the 1974 debris torrent; the downstream gabion sites (II and III) did not appear greatly affected by the debris torrent. Although it was the intention of this study to provide results that could be extrapolated to other landslide-damaged streams, such extrapolation should only be made with caution.

5.1 Site Stability

Gabions at 1% slope gradient reaches in this study were beginning to stabilize entrapped gravels in the second year after considerable changes in site morphology in the first year. Gravel scour and aggradation was high at all three gabion sites during stormflows in the first winter after construction (Table 1). The changes in stream morphology caused by gabion installation induced scour and fill as the stream approached a new equilibrium (Reeves and Roelofs 1982). Reshaping of gabion sites by stormflows was expected to decrease over time, owing to self-armouring of scoured high-flow channels that developed after gabion installation. Streambed configurations appeared to have achieved an equilibrium in the second year, especially evident at the sites at 1% slope gradient (Treatment Sites II and III; Figures 10 and 11).

A state of dynamic equilibrium was evident over some of the study sites when gravels from further upstream replaced those being scoured downstream. Dynamic equilibrium resulted in gravel scour being registered by vertical erosion monitors, although no net change in streambed configuration occurred. A successful gabion would reduce the depth of gravel scour to minimize the physical removal of salmonid eggs (see 5.3). Success in reducing gravel scour was evident at the two lower treatment sites (II and III) over the second season of winter stormflows; the average scour at Treatment Sites II and III was about the same as the average of the control sites (4-5 cm; Table 1). This depth of scour may have directly affected up to 15% of the pink eggs (see 5.3). However, mortality through scour was only one of several factors that further reduced pink egg survival to approximately 10% (Table 10). It would appear that attempting to stabilize gravel more than the 4-5 cm of scour found in control sites (Table 1) may become detrimental to overall salmonid egg survival, owing to tradeoffs with beneficial aspects of gravel scour. Engels (1975) concluded that:

> Seeking total stability of a gravel bar becomes self-defeating, since such permanence can only be obtained by reducing stream velocities to a point where the utility of a gravel bar as a spawning area is negated due to its being completely buried under fine sand and silt. The optimum goal -- that of providing reasonable stability with water velocities still high enough to prevent burial under sand and silt -- requires approximating the natural equilibrium condition noted above [a state of semi- or dynamic-equilibrium]. Under such conditions, gradual scour of a gravel bed is considered both <u>necessary</u> and <u>normal</u>, and periodic replenishment of the gravel supply must be considered as a normal maintenance expense.

Gravel scour at the upper 3% slope gradient Treatment Site I remained above average (12 cm) in the second year. The substantial decrease in local streambed gradients at the gabion sites (Table 3) probably was responsible for part of the stabilization effect evident at the lower two treatment sites (II and III). By reducing the local slope, gabions reduce the shear stress at the water/gravel interface, causing gravel deposition (Lisle 1981). Although the local streambed gradient of Treatment Site I also decreased after gabion installation, the high stormflow energy at

this 3% slope gradient site was probably sufficient to produce excessive scour, even at these reduced local gradients. Some of this scour in the second year may have been induced from an event in August 1983, which severely changed the configuration of Treatment Site I.

The apparent "failure" of Treatment Site I was a consequence of natural stream dynamics in this previously destabilized system. Two new channels 40 m downstream of the gabions were formed, one during the 1981-82 winter floods, the second during the 1982-83 winter floods. The steep slope gradient at the upstream end of these new channels was maintained by old buried logs and boulders until the August 1983 flood; these gave way, resulting in a more gentle slope gradient. The effect of this was not unlike "nick point migration" (L. Beaven, personal communication);[6] the steep slope gradient (nick point) portion of the stream channel moved progressively upstream as materials at the base of this nick point were washed downstream. This nick point migration was temporarily halted at the lower gabion at Treatment Site I. Lack of the support provided prior to the flood by streambed material against the downstream edge of this gabion enabled the gabion to start rolling into its now-enlarged plunge pool (Figure 9); the height of the waterfall over this lower gabion increased from the previous 40 cm to the new height of 90 cm. The gabion responded to these changes by bowing approximately 1 m downstream and rolling approximately 20° off the vertical. Should this gabion and the upstream one fail progressively, this nick point will migrate upstream and endanger the foundation of a log bridge 20 m above the upper gabion.

One problem with the V-shaped gabion configuration was that of bank scour. Water changed direction when encountering gabions, flowing perpendicularly across them. This introduced a lateral component, directing streamflow towards the banks. Stormflows resulted in

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[6] L. Beaven, Fluvial Geomorphologist, Fish/Forestry Interaction Program, Queen Charlotte City, B.C.

considerable bank erosion at the downstream corners of the gabion wings. Riprap placement at strategic points alleviated this problem at the lower two treatment sites (II and III). The nick point migration at the upper Treatment Site I removed riprap, exposing the two lateral corners to subsequent erosion (Figure 9).

5.2 Gravel Quality

Gabions in this study were successful in creating high quality salmonid embryo and alevin incubational properties in their entrapped gravels. These high quality incubational properties included suitable: 1) intragravel dissolved oxygen content, 2) subsurface water velocities for oxygen provision and metabolic waste removal, and 3) salmonid fry access to surface waters for emergence. These properties are not necessarily those that are conducive to adult spawning, as discussed in 5.2.1. Gabions facilitated the exchange of surface/intragravel waters necessary to meet these criteria by increasing channel roughness. Vaux (1962, 1968) suggested the factors that controlled this interchange included: 1) the stream surface profile, 2) gravel permeabilities, 3) gravel bed depth, and 4) irregularity of the streambed surface. His examination of three cases of streambed profile indicated: 1) no interchange with a straight surface, 2) water flowed out of the gravel at a concave surface, and 3) water flowed into the gravel at a convex surface.

Results of intragravel oxygen measurements of this study were in agreement with the above findings of Vaux (1962, 1968); intragravel dissolved oxygen was maintained at a high concentration at the upper treatment site (I) and significantly improved with gabion installation at Treatment Sites II and III (Tables 5 and 6). Where there was only one convex region of the stream profiles per gabion site prior to gabion installation at the tail (downstream end) of the upstream pool, there were three convex regions per site after installation: 1) at the tail of the initial pool above the upstream gabions, 2) at the tail of the plunge pool between the gabions, and 3) at the tail of the plunge pool downstream of the lower gabions (Figures 9, 10, and 11). Streamflow turbulence was

another factor found to facilitate this surface/intragravel water interchange (Vaux 1962; Wickett 1962). Turbulence was provided at the gabion sites by the plunge over the gabions.

Gravel composition and intragravel permeability are interrelated factors which affected the supply of intragravel dissolved oxygen to incubating salmonid eggs and alevins. The proportion of fine sediments in stream gravels has been inversely correlated with intragravel dissolved oxygen (McNeil 1969; Phillips 1971; Langer 1974; Skaugset 1980). This relationship was a result of a reduced intragravel permeability (and thereby reduced intragravel water velocity) observed when increased fine sediments filled intragravel pore spaces (Wickett 1962; Cooper 1974). The negative effects of fine sediments on salmonid egg survival have been extensively documented (Merrell 1962; Shelton and Pollack 1966; Bjornn 1968; Cooper 1974; Koski 1975; Tagart 1976; Slaney et al. 1977), and summarized by Cederholm and Salo (1979). In addition to fine sediments reducing the permeability of the gravels (Wickett 1962), they also may obstruct access to the surface waters for emerging fry (Slaney et al. 1977). The effect of gabion installation on the composition and permeability of entrapped streambed gravels was not clearly demonstrated in this study; improvement of gravel quality was inconsistent both between parameters measured and between gabion sites, as discussed separately below.

5.2.1 Treatment Site I

Changes in gravel quality at Treatment Site I could not be determined, owing to the coarse nature of streambed materials prior to gabion installation; coarse substrate precluded sampling of intragravel permeability and gravel composition before gabion installation. Sediment trap analysis was also unavailable, since all traps at Treatment Site I were scoured out during winter stormflows.

The quality of gravel at Treatment Site I one year after gabion installation can be compared to that at other sites. The proportion of fines in samples at Treatment Site I was lower than at five other study sites (Figure 14). On the other hand, Treatment Site I had more coarse material than all of the other study sites sampled except its "marginal habitat" Control IA (Figure 13). Permeability 1 year after installation here was above the average of the six sites sampled before installation but below the average of the eight sites sampled 1 year after installation (Table 5). These results suggest that both low fines and low permeability existed here after installation, in contrast to the observations of Cooper (1974) and Wickett (1962) that a low proportion of fines result in high permeability. Because of the high spatial variability in gravel composition found in streambeds (Scrivener and Brownlee 1982), the gravel sample size here (n = 5) may have been insufficient to represent the whole site. The problem of seasonal variability in intragravel permeability and gravel composition (Scrivener and Brownlee 1982) was minimized in the present study with the sampling of both these parameters during the summers.

5.2.2 Treatment Site II

Three gravel quality parameters indicated that gabions improved the quality of salmonid egg incubation habitat at Treatment Site II. Intragravel permeability and dissolved oxygen both increased after gabion installation (see 4.1.2). Sediment trap analysis suggested there was less sedimentation here than at its control sites (IIA and IIB; Figure 15). These improvements were not reflected in the amount of fine sediments in gravel samples at this site. No change was detected with gabion installation, perhaps a result of the initially lower proportion of fines at Treatment Site II before gabion installation than at most other sites (Figure 14). Where the proportion of fines was initially high, such as at

Treatment Site III, the amount of flushing by spawning fish and gravel scour reduced fines to the low proportions found at Treatment Site II (Figure 14).

5.2.3 Treatment Site III

Three of the gravel quality parameters measured indicated the gabions at Treatment Site III resulted in increased quality of incubational habitat. The fine sediments found in gravel samples decreased with gabion installation (Figure 14). However, the reductions in fines in gravel samples was not in agreement with sediment trap results. Greater fine sediment accumulation was found in sediment traps at Treatment Site III when compared to that of Control Sites IIIA and IIIB (Figure 15). This contradiction may be an artifact of the sediment trap results. Since many of the traps were lost from scouring, those recovered and analyzed were necessarily in depositional areas and low-scour areas (<5 cm). The higher sediment accumulations at Treatment Site III may have resulted from a higher proportion of traps recovered from depositional areas than that of its control sites (IIIA and IIIB). Both intragravel permeability and dissolved oxygen increased after gabion installation (Tables 5, 6 and 7).

Different processes that affect gravel quality probably were interacting on the study sites. Natural scour and fill processes during stormflows sort gravels behind "roughness elements" such as gabions (Lisle 1981). During the receding limb of the hydrograph, upwelling behind stream obstructions keep fine sediments in suspension while coarser gravels deposit in the previously scoured areas. The redd-digging process of spawning salmon also can reduce the proportion of fine sediments in spawning gravels (McNeil and Ahnell 1964; Shapely and Bishop 1965). Although scour during freshets may be significant in flushing fines in the upper 5-6 cm (Year 2 average; Table 1), spawning activity may flush gravels deeper than the 25 cm insertion depth of the permeability standpipe. The

flushing action of up to about 150 pinks per site (Table 8) may be responsible for the apparent increases in permeability observed in Control Sites IIIA and IIIB from summer 1982 to summer 1983. The dominance of the even year pink run allowed 20 months of fines accumulation prior to the 1982 sampling but only 8 months accumulation prior to 1983 sampling. A similar seasonal increase in permeability with spawning activity was found in Carnation Creek for the pre-logging period (Scrivener and Brownlee 1982). This coincided with a seasonal trend of decreased fines during spawning and winter stormflows and an accumulation of fines over summer.

5.3 Spawner Use

The gabions succeeded in producing gravel beds suitable for salmon spawning, as indicated by both spawner observations and calculated probability-of-use (see 4.3.3, 4.4, and 4.4.1). The observed spawning activity indicated gabions had variable effects on site usage compared to controls. Treatment Site I was upstream of pink and chum distribution, but had greater coho usage than its control sites (IA and IB; Table 8). Pink usage at Treatment Site II was greater than its marginal control (IIA), but less than its prime control (IIB; Table 8). The greater abundance of pink and chum spawners in lower reaches of Sachs Creek (Figure 16) was probably the cause of lower observed use of Treatment Site III than its control sites (IIIA and IIIB; Table 8). The higher use of Treatment Site III than Treatment Site II may be a result of the "drain rock" on the latter site not being of a size attractive to pink spawners.

Probability-of-use calculations for Treatment Sites I and II and their controls were in agreement with the observed spawning activity (Tables 8 and 9). However, the calculated probability-of-use for Treatment Site III compared to that of its controls was not in agreement with the relationship of observed spawner usage of Treatment Site III compared to that of its controls. Where observed pink spawner usage of Treatment Site III was 0.5 that of its control IIIB (Table 8), its calculated probability-of-use was slightly greater than this same control

(Table 9). The explanation for this contradiction probably lies in the spawner distribution within the stream. Less than 0.5 as many pink spawners were available to spawn on Treatment Site III as were available at Control Site IIIB (about 4.8 and 11 fish per metre respectively; Figure 16). Adjusting the observed use of Treatment Site III by the inverse of the relationship of spawner availability (2.3) would bring observed use in agreement with probability-of-use. Similar relationships were found between Treatment Site III and Control Sites IIB and IIIA, as explained below:

i. The ratios of observed spawning activity of Control Sites IIB and IIIA compared to that of Treatment Site III were 0.90 and 1.8 respectively (Table 8).

ii. The ratios of spawner availability on Control Sites IIB and IIIA compared to Treatment Site III were approximately 0.64 and 1.3 respectively (Figure 16).

iii. To account for differences in spawner availability, the ratios of observed spawning activity in (i) should be multiplied by the inverse of the ratios of spawner availability in (ii).

iv. The ratios of observed spawner activity, when adjusted as in (iii), approximate the ratios of the probability-of-use of Control Sites IIB and IIIA compared to that of Treatment Site III (both at 1.4; Table 9).

This suggests that distance upstream of the estuary affects spawner distribution independently of other probability-of-use features. Probability-of-use calculations should therefore incorporate distance upstream of the estuary as a usage criteria.

Treatment Site I may not have had spawning habitat suitable for pink salmon (Table 9), owing to its 3% steep slope gradient and resultant high energy of stormflows, even if pink and chum spawners could have reached it (Figure 7). The likelihood of ever creating artificial spawning habitat in steep gradient, upper reaches of "flashy" Queen Charlotte Islands streams is poor. However, in reaches having lower slope gradients (1-2%), gabions can create habitat suitable for pink and chum spawning.

5.4 Egg Survival

Gabions in this study did not improve early survival of pink and chum salmon in the first year after their installation. In contrast, a study in Washington suggested that gabions there improved chum egg survival during their first year of operation (Gerke 1974). The average pink salmon egg survival to December at Treatment Site III and its two Control Sites IIIA and IIIB (11, 11, and 7.9% respectively; Table 10) lie within the range of other coastal streams. Frequently, 95% of eggs deposited by pink and chum salmon die before the fry emerge from spawning gravels (Merrell 1962; McNeil 1966, 1969; Dill 1969; Langer 1974).

The substantial difference in pink salmon egg survival calculated by the two indices used in this study (relative egg survival was on average 68% higher than the egg survival from potential egg deposition; December values, Table 10) indicated a high degree of egg loss from the gravels. The relative survival index did not account for these egg losses. Both biological and physical factors affect salmonid egg survival. Biological factors include predation by birds, fish, and insects, non-fertilization of egg, and redd superimposition. Redd superimposition egg losses result from late arrival spawners digging new redds on top of previously constructed redds. Physical-chemical factors that affect salmonid egg survival include gravel scour and gravel quality. Extreme winter low flows and freezing were not considered a problem in Sachs Creek in 1982-83. All of these factors have substantially reduced egg survival in events described elsewhere (McNeil 1969). Redd superimposition occurred at about 70% of the stations sampled in the two control sites (IIIA and IIIB) and at about 20% of the stations sampled at Treatment Site III (Table 12). This suggested that even for an average size pink run, spawning habitat was limiting at Sachs Creek. Less redd superimposition occurred at Treatment Site III, probably due to it being further upstream beyond the peak density area for pink spawners (Figure 16). In addition to the physical removal of previously spawned eggs, redd superimposition also may have: 1) shocked the very sensitive eggs that had not developed to the eyed stage, or 2) if the eggs were eyed, redistributed them vertically, making them more vulnerable to subsequent loss through gravel scour.

Egg loss through gravel scour would be related to the depth at which the eggs were deposited and the depth to which the gravels were scoured. Live eggs were distributed fairly evenly down to a depth of 40 cm, but dead eggs were more common near the surface (70% in the top 20 cm; Table 13). Observations from the Kodiak archipelago suggest that pinks there initially deposited eggs between 10 cm and 25 cm (K. Manthey, personal communication);[7] alteration of similar distributions by gravel scour, aggradation, or redd superimposition probably produced the distribution found in this study. The predominance of dead eggs near the surface suggested redd superimposition was at least partially responsible, with mortality a consequence of the jarring involved.

The depth of gravel scour in several "flashy" Queen Charlotte Islands streams tend to be high. Preliminary egg depth measurements by FFIP suggested that of the 65 stations measured, 15-20% of the coho eggs and 30% of the chum eggs may have been directly affected by gravel scour (D. Tripp, personal communication).[8] Gravel scour in the control sites at Sachs Creek averaged 5.1 cm over winter in the first year and 4.5 cm in the second year (Table 1). Gravel scour may therefore have accounted for up to 15% of the pink egg mortality in the control sites at Sachs Creek for these years (Table 13). Although it appeared that after 2 years the gabions here did not reduce egg loss as a result of reduced gravel scour (Table 1), the quality of the gravel for incubation of the remaining eggs ($>85\%$) and alevins was improved by gabion installation (Table 17).

In this study, intragravel dissolved oxygen was found to be significantly correlated with the index of relative egg survival (Table 13). This relationship was not detected with the index of survival from potential deposition, probably owing to the overwhelming influence of

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[7] K. Manthey, Area Management Biologist, Kodiak Area, Alaska Dept. Fish and Game.

[8] D. Tripp, Biologist, Fish/Forestry Interaction Program, Vancouver, B.C.

egg loss (>80%) on this index; i.e., oxygen deprivation appeared a significant source of mortality to those eggs that had not been physically removed from the gravels (<20%). Other variables such as intragravel permeability and depth of gravel scour may indeed have affected egg survival in Sachs Creek, but the complex nature (with possible synergistic effects) in which all these factors interrelate could not be modeled with the multiple regression analysis applied.

5.5 Juvenile Use

Two main areas of benefits were offered by gabions in this study: 1) an improvement in pink and chum salmon spawning/incubation habitat, and 2) an improvement in juvenile coho salmon and rainbow trout (or steelhead) rearing habitat. Since juvenile salmonid densities were not measured prior to gabion installation, evidence for improvement in rearing habitat was indicated through deduction.

Substantially higher juvenile densities were found at gabion sites than at control sites (Table 14). High juvenile densities at the gabion sites in this study were in agreement with increased coho densities at gabion sites (here used as current deflectors) placed on other coastal streams (Ward and Slaney 1981). The ability of gabion sites to accommodate higher juvenile densities was indicated by the length frequencies of the 0+ coho. In other studies, coho size was inversely correlated to their density (Fraser 1969). One could therefore expect that coho lengths at gabion sites (higher juvenile densities) would be less than at the control sites (lower densities). However, coho lengths at the gabion sites tended to be greater than at control sites (significantly greater than three of the six control sites; $p < .05$; Table 16 and Figure 18). The ability of gabion sites to accommodate more and larger juveniles suggest that physical differences at the sites are responsible for this greater use. If it can be shown that gabions produced these physical differences, one can conclude that gabions improved rearing habitat.

Salmonid rearing habitat requirements varied between species and changed with season. In inter-species territorial confrontations, Hartman (1965) found that coho were more successful in lower velocity "pools" and steelhead were more successful in higher velocity "riffles". Bustard and Narver (1975a) found that as stream temperatures decreased in winter, these feeding positions described by Hartman (1965) were exchanged for habitat closer to cover. In winter, 0+ coho were associated more with organic cover, and 0+ steelhead with rubble (Bustard and Narver 1975b; Ward and Slaney 1981). The present study suggested that gabions increased rearing habitat diversity because two additional pool-riffle sequences were created at each site (see 4.1.1). This diversity facilitated inter-species resource partitioning by providing separate areas best-suited for each species. At the gabion sites both riprap and boulder rubble below the plunge pools provided some winter habitat for steelhead. Placement of boulders in coastal streams has been found to improve steelhead winter habitat (Ward and Slaney 1979). The nooks and crannies within the gabion structures themselves similarly provided cover. For coho winter habitat, gabion sites provided some organic debris cover. However, the addition of rootwads anchored in the plunge pools would greatly augment juvenile coho winter and summer habitat (G. Hartman, personal communication).[9]

The flood on 2 August, 1983, in Sachs Creek provided an unexpected opportunity to examine flood related juvenile salmonid population dynamics. As anticipated, the largest decrease in coho population (-92%) occurred at the uppermost Treatment Site I (Table 15) where energy of the stormflow was greater than at other sites. This was suggested by the 3% steep slope gradient and substantial changes in site configuration (see Section 5). The 51% decrease in juvenile coho population at the other two treatment sites (II and III) was less than the 84% decrease at the marginal control sites (IIA and IIIA) but greater than the 21% decrease at

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[9] G. Hartman, Co-ordinator, Carnation Creek Watershed Studies, Pacific Biological Station, Nanaimo, B.C.

the prime spawning habitat control sites (IIB and IIB; Table 15). Despite these major changes in coho populations, many juveniles resumed their feeding stations on the same sites after the flood. The proportion of juveniles marked in the pre-flood sampling that were accounted for during the post-flood sampling ranged from about 30 to 60% between the sites (Table 15); that of the two gabion sites again was between that of their control sites (Table 15).

5.6 Summary of Positive and Negative Effects of Gabions

The effects of gabion installation on the physical-chemical and biological parameters measured on study sites in Sachs Creek were briefly summarized in Table 17. In relation to salmonid production, the beneficial effects of gabions on gravel scour and streambed slope gradients outweighed the negative three to one. Similarly, gravel quality parameters showing beneficial effects of gabions outweighed those with negative by eight to two.

In summarizing the effects of gabions on spawner use (Table 17), the observed spawning uses were adjusted for longitudinal spawner distribution (see 5.2.3). The calculated probability-of-use was entered unadjusted. The effects of gabions on suitability of spawning habitat was variable with one positive indicator, three neutral, and two negative.

Both of the egg survival indices showed beneficial effects of gabions (Table 17). The indication of 11 positive to three negative physical-chemical effects of gabions (Table 17) suggest that future egg survival at gabion sites may be expected to be greater than that observed in this study in the first year of operation. Similarly, only beneficial effects of gabions on juvenile salmonid production were found by this study.

In summing the positive and negative attributes per site, Treatment Site I ranked lowest with five positive to three negative indicators, probably owing to the effects of a steep (3%) slope gradient. Treatment Sites II (seven positive to one negative) and III (eight to one) indicated there were substantial site improvements with gabion installation at these sites. The overall ratio of 20 positive to five negative suggest that

TABLE 17. A summary of the effects of gabion installation on major physical-chemical conditions and their relation to salmonid production in Sachs Creek

Parameter	Treatment I	Treatment II	Treatment III
Site stability:			
Scour (Year 2)	>control (-)	=control (=)	=controls (=)
Slope gradient	reduced (+)	reduced (+)	reduced (+)
Gravel quality:			
Dissolved oxygen	decreased (-)	increased (+)	increased (+)
Permeability	-----	increased (+)	=controls (=)
Sites for spawning	increased (+)	increased (+)	increased (+)
Fines	low (=)	same (=)	large decrease (+)
Sediments in traps	-----	controls (+)	>controls (-)
Spawner use:			
Observed	>cntrls:coho (+)	<controls (-)	between cntrls (=)
Probability-of-use	<controls (-)	betw'n cntrls (=)	between cntrls (=)
Egg survival:			
Relative index	-----	-----	>controls (+)
Potential index	-----	-----	>controls (+)
Juvenile use:			
Density	> controls (+)	> controls (+)	> controls (+)
Pools riffles	> controls (+)	> controls (+)	> controls (+)
Totals: Positive	5	7	8
Neutral	1	3	4
Negative	3	1	1
Grand total:	Positive = 20	Negative = 5	

gabions may be an effective way to rehabilitate streams. However, recommendations for further application may be determined by their cost effectiveness.

5.7 Preliminary Benefit Cost Analysis

The costs of the project were divided into six categories, as listed in Table 18. There was an obvious trend of decreasing installation costs with experience of installation (from $5200 to $3800 to $3000; first to last) for the three treatment sites. The cost per metre of gabion installed similarly decreased with experience (from $105/m to $89/m to $85/m).

The costs were not representative of what should be expected in an operational sense. The contractor employed to excavate the sites discounted his equipment time 30%. The project was billed a rate of $50/hour rather than the normal $70/hour for the excavator. Considerable cost was also saved by using slack time on the excavator; the excavator operator loaded and hauled gravel during the periods he could not do instream work. Many contractors would have charged for both machines. Resultant contractor costs, therefore, were estimated at about 50% of actual costs. The projected non-discounted costs were included in Table 18.

Manpower for gabion construction was supplied through Fisheries Employment Bridging Assistance Program (Project No. 566). While this assistance made this project possible, considerable reduction in man-days probably would have occurred if a non-"job creation" labour force had been used. Some loss of productivity was also evident through short work days, owing to extensive travel time. It was estimated that trained manpower would have completed the job in two-thirds of the time expended. A realistic cost for hired manpower on the Queen Charlotte Islands would be $80 per day (1982). Using these figures, the projected manpower costs for gabion installation are given in Table 18.

TABLE 18. Gabion installation costs at Sachs Creek

Treatment Site #:	I	II	III	Total
Dates worked August 1982:	7-23	9-17	24-29	
1) Gabions: length (m):	43	50	35	128
Cost delivered:	$ 954	$1086	$ 882	$ 2 922
2) Excavation: hours:	15.5	20	12	47.5
@ $50/hour: costs:	$ 775	$1000	$ 600	$ 2 375
3) Spawning gravel:				
Hauling: hours:	11.5	10	5.5	27
@ $50/hour: cost:	$ 575	$ 500	$ 275	$ 1 350
Distributing: hours:	5	6	4	15
@ $50/hour: cost:	$ 250	$ 300	$ 200	$ 750
4) Equipment transport:	$ 58	$ 58	$ 58	$ 174
5) Sorted rock-delivered:	$ 0	950	$ 400	$ 1 350
6) Labour: man-days:	27	30	14	71
@ $45/man-day: cost:	$1215	$1350	630	$ 3 195
Total cost:	$3827	$5244	$2985	$12 057
Total cost per gabion Length (per m):	$ 89	$ 105	$ 85	$ 94
Projected costs:				
Contractor's discount:	$1658	$1858	$1133	$ 4 649
Labour: man-days:	18	20	10	48
Cost @ $80/day:	$1439	$1600	$ 800	$ 3 840
Total projected costs:	$5709	$7352	$4288	$17 349

Several hundred cubic metres of gravel and rock were used on the gabion sites. The majority of this gravel was donated from a nearby MacMillan Bloedel gravel pit. This material was unsorted river run gravel. Initially, concern was expressed that the fines component of the pit gravel was high and could influence egg survival. To prevent this, 21 m^3 of sorted "drain rock" (between 2 cm and 15 cm diameter) was purchased and distributed over a partially surcharged Treatment Site II. The high cost of the drain rock (approximately $600 delivered) deterred further use of this material on Treatment Sites I and III. The drain rock may have been responsible for the lower proportion (dilution) of fines in the surcharged materials of Treatment Site II compared with Treatment Sites I and especially III (September 1982; Figure 14). The ability of the stream to remove these fines by the June 1983 sampling would suggest that the overall dilution effect of this drain rock on egg survival was negligible.

In filling the gabions, local rock larger than 10 cm diameter was used before commercially sorted rock was purchased. Although there was sufficient local material at Treatment Site I, $350 and $400 worth of sorted rock was needed at Treatment Sites II and III respectively (Table 18).

The cost effectiveness of gabion installation in Sachs Creek remains preliminary to date. Although the costs are known, the increase in fish production and the longevity of the gabions are not. Gabion longevity is dependent on both the integrity of the structure and the resistance of the wire mesh to abrasion and rust. Similar structures have withstood floods of 100-year return periods in Oregon (Anderson 1981). Longevity of the gabions in this study may be dependent on the local slope gradient of the stream. The dynamic nature of stream morphology in higher gradient reaches (>2%), especially those rendered unstable from poor streamside logging or debris torrents as at Treatment Site I (see Section 5), reduced the likelihood of adequate structure longevity. However, the ability of structures in the 1% slope gradient reaches to withstand the August 1983 flood without shifting suggested that gabions at low slope gradient sites

may have a longevity of a few decades. Abrasion also was more prevalent at the higher gradient gabion site in this study (Treatment Site I) than at the lower gabions (Treatment Sites II and III). Abrasion was found only on the galvanized coating on the upstream exposed portions of the gabion mesh. Rusting of the mesh was not evident but may limit the useful life of the structures.

The economic values of some of the benefits and costs of gabions were not calculated because of the uncertain nature of these factors. One such cost was fine sediment input during gabion construction. The suspended sediments were estimated to have exceeded 400 ppm (J. Lamb, personal communication)[10] during streambed excavation. Settlement of the sediments was rapid, with accumulations up to 2 cm deep in backwater areas immediately downstream of the sites. These were flushed from the system during the first minor stormflow. The effects here were similar to those described for excavation in other coastal streams by Ward and Slaney (1979).

Benefits of gabions described in previous sections above included anticipated increases in salmonid egg-to-fry survival and increases in juvenile salmonid summer densities and rearing habitat. In addition, many adult salmon were observed "holding" or resting in water ponded upstream of the gabions in autumn 1982 and 1983. Another benefit may be an increase in stream benthos productivity expected with riparian vegetation removal during gabion installation; the localized increased sunlight input to this northern cold-water stream may improve algal and benthos production, providing more food for rearing juvenile salmonids (Dubowits 1979). Although gabions may make significant contributions to fish production through the benefits described above, it is only through anticipated increases in pink salmon egg survival that the following benefit/cost analysis was made. The actual cost efficiency of gabions would probably be greater than the following analysis suggests if the other benefits of gabions were included.

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[10] J. Lamb, Habitat Protection, Dept. Fisheries and Oceans, Nanaimo, B.C.

A benefit/cost analysis was made to determine what production goals were required to offset gabion construction costs, with sensitivity expressed over their expected ranges. Treatment Site III was used for this analysis because: 1) it was the last and hence least expensive gabion site, having the benefit of previous installation experience; and 2) it had sufficient spawner usage to enable egg sampling. Criteria considered in the analysis are outlined below.

5.7.1 Benefits

i. Pink spawner use of Treatment Site III was 60 females (120 adults) in 1982. After adjustment for effects of longitudinal spawner distribution, actual usage of Treatment Site III was intermediate between that of its controls (see 5.2.3). Hence, benefits from increased spawner usage were not included in the benefit/cost analysis.

ii. Egg survival within Treatment Site III appeared higher than that of both Control Sites IIIA and IIIB. Increases in average egg survival were assumed to have an equal effect on increases of returning adults (e.g., a 100% increase in egg survival would yield an additional 100% of the original number of fish spawning on the site [120 adults] and returning as adults). An exploitation rate for adult pink salmon returning to the east coast of the Queen Charlotte Islands averaged 56% over the past 10 years (S. Wright, personal communication).[11]

iii. Current wholesale prices of pink salmon were assumed to be $8.87 per piece for net caught, and $6.00 per piece for troll caught in 1982 dollars.[11] These figures were based on the 1976 provincial catch and adjusted for

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11 S. Wright, Evaluation Economist, Dept. Fisheries and Oceans, Vancouver, B.C.

inflation to 1982 values. Of the pink salmon caught in the Queen Charlotte Islands area, 96% were net caught and 4% were troll caught. The adjusted wholesale price averaged $8.76 per piece.

iv. Over the lifespan of the gabions, an equal increase in pink adults was assumed forthcoming every other year. Analysis sensitivity was shown for longevities of 6, 12, and 18 years.

5.7.2 Costs

i. The initial construction cost of Treatment Site III projected to reflect real costs was used ($4288; Table 18). However, construction costs may continue to decrease with experience.

ii. Once installed, gabion sites were expected to require no additional work and maintenance costs were assumed zero.

iii. Subsequent costs included harvesting and processing of the increase in returning adults. Harvesting costs in 1982 dollars[12] were $0.61 per piece for troll caught and $0.19 per piece for net caught, averaging $0.21 per piece (adjusted for proportion net and troll caught; see 5.7). Processing costs were $2.38 per piece for troll caught and $2.75 per piece for net caught, averaging $2.75 per piece. Processing costs included acquisition, in-plant processing, and marketing costs. The combined harvesting and processing costs averaged $2.95 per piece.

A discounting rate of 10%, with sensitivity at 5 and 15%, was used for both costs and benefits accrued over the gabion lifespans shown. This procedure brought future values to present value. If interest rates were maintained at levels lower than 10%, the future

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12 Ibid.

net benefits indicated in this study would be conservative to what may be expected (Table 19). Similarly, if the net values rose as a result of price increases after all captial costs were incurred during construction, future benefits would be greater than expected.

Increases in returning adult pink salmon required to offset gabion construction costs are summarized in Table 19. At a 10% discount rate with a gabion longevity of 12 seasons, 375 fish additional to the 120 initially spawning on the site are required bienially (major pink runs are on even years only). A production of this magnitude (about four times natural survival) may be attainable for gabion sites, a result of improvements of gravel quality, with anticipated increases in egg-to-fry survival as discussed above. Achievement of cost effectiveness becomes more probable at lower interest rates and greater longevities (Table 19) and when benefits of gabions other than increases in pink salmon egg-to-fry survival are also considered. Lack of higher spawner usage of the gabion sites (Table 17) suggested that no benefits would be derived through effects of gabions on spawning habitat. However, gabion sites with fewer spawners would require still greater improvements in egg-to-fry survival to offset construction costs. The assumption that egg-to-fry survival was the limiting factor in smolt production appeared reasonable, because of the "immediate" seaward migration of fry emerging from the spawning gravels. However, mortality in the ocean may yield a disproportionately lower return in adults for increase in smolt production (Peterman 1982).

TABLE 19. Increases in returning pinks required to offset installation costs for Treatment Site III at Sachs Creek

	Additional number of returning adults required biennially to recover construction costs[a]					
	Number of fish			Relative increase[b]		
Discount rate:	5%	10%	15%	5%	10%	15%
Gabion longevity						
6 years	418	520	632	348%	433%	527%
12 years	273	375	495	228%	312%	413%
18 years	217	325	452	180%	271%	377%

[a] Calculations of required returns are discussed in Appendix B.
[b] Increase in production expressed as percent of the initial 120 spawners on the site in 1982.

6. CONCLUSIONS AND RECOMMENDATIONS

Gabion weirs met the five criteria required of a successful stream rehabilitation technique as outlined early in Section 5:

i. Gabion weirs surcharged with gravel created streambed configurations yielding moderate quality spawning habitat for pink and chum salmon in sites at 1% slope gradient reaches. This was demonstrated through both observed spawner usage and calculated probability-of-use. Although another site at 3% slope gradient was used by coho spawners, it was not suitable for pink spawners.

ii. Longitudinal pink salmon distribution was independent of other probability-of-use features. Future site evaluations should include distance upstream of the estuary as a probability-of-use criterion.

iii. Stability of gravels entrapped by the gabions at the two 1% slope gradient sites was demonstrated in the second year after considerable site reshaping by stormflows in the first year. However, the short duration of this study precluded conclusions on gravel stability at gabion sites during major stormflow events. The gabion site at 3% slope gradient failed to stabilize gravels, because of the high energy of stormflows there.

iv. Quality of the surcharged and natural gravels entrapped by the gabion sites was conducive to high egg-to-fry survival. Intragravel dissolved oxygen and gravel composition measurements indicated either improved or good incubational habitat. However, intragravel permeability and sedimentation measurements were inconsistent in evaluating this habitat. The apparent "stability" at the gabion sites at 1% slope gradient in the second year suggested that the high egg survival demonstrated here during an "unstable" first year would yield substantial increases in the future.

v. Juvenile salmonid rearing habitat was created with the development of two additional pool/riffle sequences per gabion site. The good quality of this habitat was demonstrated by high juvenile densities at the gabion sites (average 1.6 per square metre) compared to the control sites (average 0.9 per square metre).

vi. Preliminary benefit/cost analysis projected the required increases in pink salmon production for various gabion longevities (e.g., approximately a 300% increase over a longevity of 12 years). Cost effectiveness may be attainable, especially at lower interest rates and greater gabion longevities, owing to the effects of high quality and stability of gravels entrapped at the gabion sites in increasing egg survival; no benefits were derived from spawner usage.

Recommendations for future application of gabion weirs adapted from the eight criteria reviewed by Moreau (1981) are as follows:

i. Select a straight stream section.

ii. Select a section wider than average channel width.

iii. The stream reach should have gradually sloping banks, preferably with an overflow (flood) plain.

iv. Local channel slope should be slight.

v. Site substrate should be slightly larger than desired.

vi. The tail of a pool is suitable if the criteria above are met.

vii. The site must have good access.

viii. Where weirs are to be placed in series, place the downstream weir such that the top of the downstream weir is level with the base of the upstream weir.

Additional recommendations suggested by this study include:

ix. Select downstream reaches within peak distributions of spawning pink salmon.

x. Limit streambed slope gradients to $< 2\%$ (as in [iv] above) in "flashy" coastal streams.

xi. Generously riprap the banks at and below the points to which the gabions are keyed, to prevent lateral bank scour around the ends of the gabions.

xii. The intergabion distance should equal at least 1.5 times the wetted width of the stream to allow sufficient length of plunge pool upstream of the entrapment area of the downstream gabion.

xiii. Splash aprons are more useful in the lateral wing regions than near the apex of the gabions.

xiv. Further research may be best directed in "fine-tuning" gabion configurations to maximize areas of prime spawning habitat.

xv. Low-cost procedures for minimizing suspended sediment release during instream excavation should be developed.

xvi. Site construction should be during an "off" pink year to allow reshaping from 1 year of stormflows and so stabilize the site prior to heavy spawner usage.

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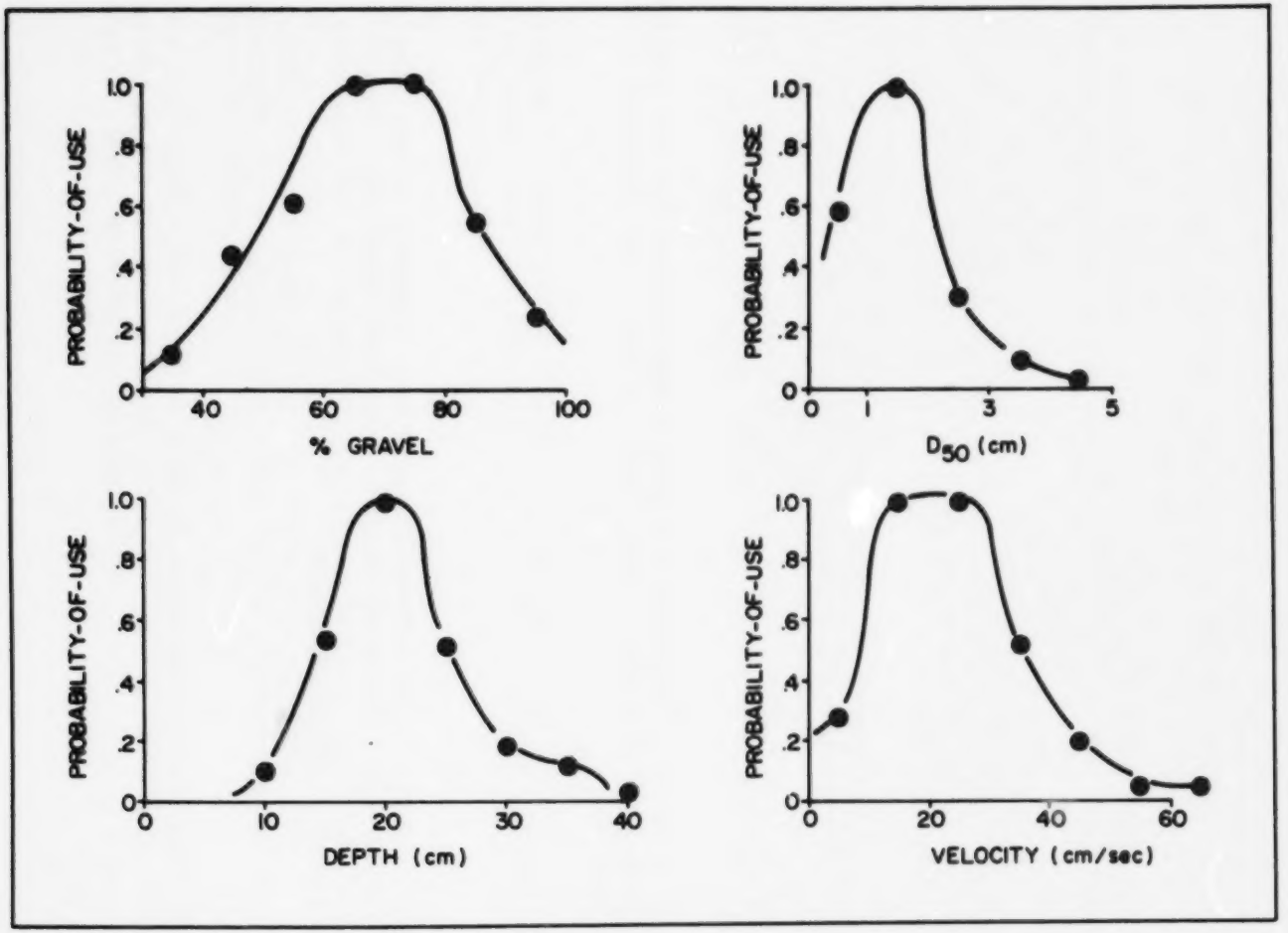


APPENDIX 1. Probability-of-use criteria of Sachs Creek pink redds (n=230)

APPENDIX 2. Calculations of benefit/cost analysis for Treatment Site III at Sachs Creek.

The increase in pink salmon production required to offset initial gabion construction costs was derived below. The average wholesale price of $8.76 per piece less the average harvesting and processing costs of $2.95 per piece yields a net benefit of $5.81 per piece (discussion and assumptions in 5.7). Discount rates of 5, 10, and 15% were applied to all values incurred after year zero to bring future values to present worth. All values were in 1982 dollars.

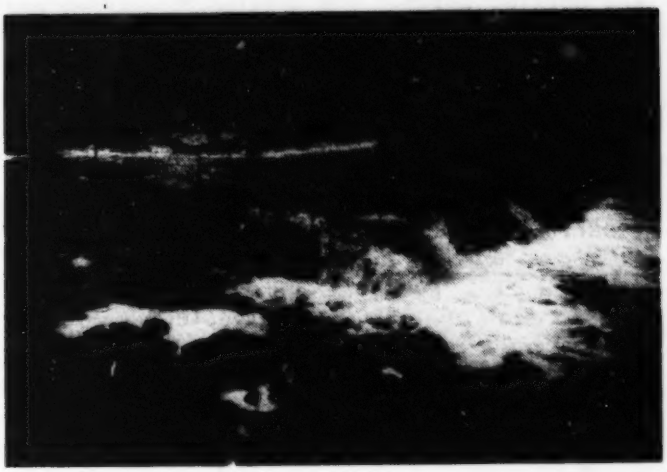
	Net benefits per fish			Additional fish required per spawning year to recover costs[a]					
				Harvested[b]			Returning[c]		
Discount Rate:	5%	10%	15%	5%	10%	15%	5%	10%	15%
Year[a]									
0	$ 0	$ 0	$ 0						
2	5.27	4.80	4.39						
4	4.78	3.97	3.32						
6	4.34	3.28	2.51						
8	3.93	2.71	1.90						
	$18.32	$14.76	$12.12	234	291	354	418	520	632
10	$ 3.57	$ 2.24	$ 1.44						
12	3.24	1.85	1.09						
14	2.93	1.53	.82						
	$28.06	$20.38	$15.47	153	210	277	273	375	495
16	$ 2.66	$ 1.26	$ .62						
18	2.41	1.05	.47						
20	2.19	.86	.36						
	$35.32	$23.55	$16.92	121	182	253	217	325	452

[a] Pink salmon adults returning in year x are the progeny of spawners in year x-2. Major pink runs are on even years only.

[b] The initial gabion costs ($4288) were divided by the sum of net benefits per fish for the desired number of years to calculate how many adults additional to the initial 120 would be required to be harvested per spawning year to recover construction costs; e.g., after discounting at 10% for 14 years the net benefits of one fish every spawning year ($20.38) yield a requirement of ($4288/$20.38 =) 210 fish every other year.

[c] The number of additional fish required for harvest are adjusted to account for an exploitation rate of 56%, e.g., 210/.56=375.

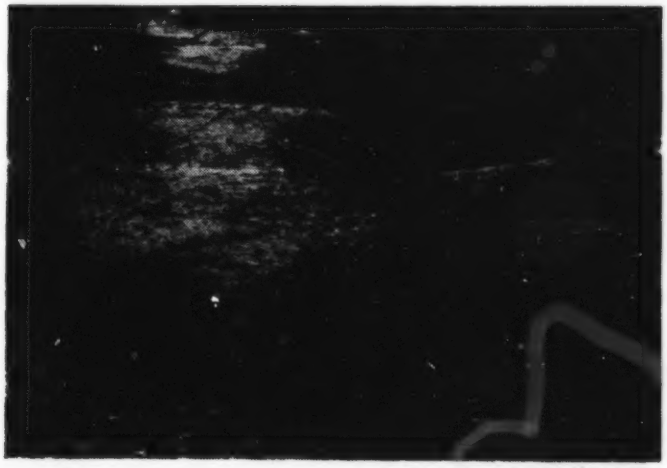
APPENDIX 3. Photographic plates of gabion sites at Sachs Creek, 1.5 years post-installation, February 1984



Treatment Site I: Note the enlarged waterfall over the downstream gabion (a result of "nickpoint migration"). Large size of substrate was a consequence of the high energy at this 3% slope gradient site.

Treatment Site I: The downstream left gabion wing that responded to the above changes by bowing approximately 1 m downstream and rolling approximately 20° into the plunge pool.

Treatment Site II: Note vigorous growth where streambank was seeded and fertilized.



Treatment Site II: Looking upstream. Note the gravel bar formed downstream of the gabions.

Treatment Site III: Note scoured bank on far side and riprap placement where gabions were keyed into the bank. The water level at this site was raised by spruce blowdowns on right of photograph and subsequent upstream gravel bar formation.

Treatment Site III: Looking upstream, the old log jam at the bottom of photograph is deflecting the stream, resulting in a deep scour pool in front.

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